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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Modelling District Heating and Cooling

Analysis of Network Costs and Configurations for a Decarbonised Heat and Cold Supply

Modelling District Heating and Cooling

Analysis of Network Costs and Configurations for a Decarbonised Heat and Cold Supply

by Luis Sánchez-García

LUND UNIVERSITY

Thesis for the degree of Doctor of Philosophy in Engineering
Thesis advisors: Prof. Dr. Urban Persson, Dr. Helge Averfalk, Dr. Erik Möllerström, Dr. Marcus Thern
Faculty opponent: Associate Professor Dr. Elisa Guelpa

To be presented, with the permission of the Faculty of Engineering of Lund University, for public criticism in the M:B lecture hall (Ole Römers väg 1, 223 63 Lund) at the Department of Energy Sciences on Thursday, the 11th of September 2025 at 10:15.

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Department of Energy Sciences
Box 118
SE–221 00 LUND
Sweden

Author(s)
Luis Sánchez-García

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Abstract
District heating and cooling is a simple but powerful technology that could contribute to decarbonising Europe's heating and cooling supply. However, its current overall penetration is minor. Furthermore, future systems could adopt different configurations with various settings of temperature levels or production location. This thesis has aimed to improve existing tools to evaluate district heating potential, apply them on a continental scale and assess the economic benefits and costs of two main types of district heating configurations.

Concerning the first topic, district heating feasibility is highly dependent on network investment costs and, therefore, their estimation is critical. One of the tools developed for this task is Persson & Werner's model, a data-lean and fast method which provides a first-order approximation. Work on this thesis first focused on improving one of the model parameters, the effective width, which indicates the necessary trench length. An extensive geographic analysis enabled the determination of new equations that relate effective width to several indicators of building density under a wide range of conditions. Furthermore, the model with the improved parameter formulations was tested, and the results show that the model reaches relatively accurate predictions in large areas but fails to deliver in small areas. Second, attention shifted to its application on a continental scale. The enhanced model was further refined to take connection rates and future heat demands into account and was later employed to estimate district heating potential in Europe. Results show that district heating could deliver a third of the heat demand by 2050.

Regarding configurations, a broad classification can be drawn between warm and cold networks. Whereas the former are able to deliver heat at the required temperatures to the consumers from a central production plant, the latter require additional decentralised temperature boosting. Both configurations present advantages and disadvantages, but few studies had attempted to quantify their economic costs. Therefore, this thesis aimed to elaborate on an economic comparison by means of a case study of the city of Bilbao, Spain. Results show that warm networks can deliver heat at a lower cost than cold networks thanks to the benefits of centralisation, such as diversity, a combination of sources, inexpensive thermal storage or lower electricity costs, and despite a more costly pipe network. Moreover, these results are robust to a series of conditions. Nonetheless, for the combined delivery of heating and cooling, both systems lead to similar costs, since the warm network requires the construction of an additional district cooling network, whilst minimal additional outlays are necessary for the cold network.

Key words
district heating, district cooling, network costs, network configurations, GIS

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A doctoral thesis at a university in Sweden takes either the form of a single, cohesive research study (monograph) or a summary of research papers (compilation thesis), which the doctoral student has written alone or together with one or several other author(s).

In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarizes the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

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Til Rasmus

Contents

List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

I **Further investigations on the Effective Width for district heating systems**

Sánchez-García, Luis; Averfalk, Helge & Persson, Urban
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II **Understanding effective width for district heating**

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III **District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth**

Fallahnejad, Mostafa; Kranzl, Lukas; Haas, Reinhard; Hummel, Marcus; Müller, Andreas; **Sánchez-García, Luis** & Persson, Urban
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IV **Feasibility of district heating in a mild climate: A comparison of warm and cold temperature networks in Bilbao**

Sánchez-García, Luis; Averfalk, Helge; Hermoso-Martínez, Nekane; Hernández-Iñarra, Patxi; Möllerström, Erik & Persson, Urban
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Author contributions

Paper I: Further investigations on the Effective Width for district heating systems

I was responsible for collecting the data, conceiving the methodology, executing the analysis, preparing the visualisation, and writing the manuscript. Each step was supervised by Urban Persson, Helge Averfalk and Erik Möllerström, who provided feedback and ideas for the paper. The final manuscript was revised by the three supervisors, who suggested improvements.

Paper II: Understanding effective width for district heating

I was responsible for collecting the data, conceiving the methodology, executing the analysis, preparing the visualisation, and writing the manuscript. Each step was supervised by Urban Persson, Helge Averfalk and Erik Möllerström, who provided feedback and ideas for the research. The final manuscript was revised by the three supervisors, who suggested improvements.

Paper III: District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth

My contribution to this paper consisted of sharing my work on effective width, discussing the methodology and reviewing the manuscript.

Paper IV: Feasibility of district heating in a mild climate: A comparison of warm and cold temperature networks in Bilbao

In discussion with my supervisors and Patxi Hernández-Iñarra, I contributed to conceptualising the study. I was then responsible for developing the methodology for estimating the costs of the main elements of a district heating system, collecting and curating the necessary data, elaborating the visualisations and writing most of the original manuscript. Urban Persson, Helge Averfalk and Erik Möllerström, as well as Sven Werner and Marcus Thern, provided invaluable feedback to the internal review and edition of the manuscript.

Publications not included in this thesis

I Möller, Bernd; Wiechers, Eva; Persson, Urban, & Sánchez-García, Luis. (2021). An empirical high-resolution geospatial model of future population distribution for assessing heat demands. [Conference Presentation]. In Lund, Henrik; Mathiesen, Brian Vad; Østergaard, Poul Alberg & Brodersen, Hans Jørgen (Editors). *7^th^ International Conference on Smart Energy Systems*, 21-22 September, Copenhagen, Denmark. http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-48175

II Meunier, Simon; Protopapadaki, Christina; Persson, Urban; Sánchez-García, Luis; Möller, Bernd; Wiechers, Eva; Schneider, Noémi Cécile Adèle, & Saelens, Dirk. (2021). *Cost and capacity analysis for representative EU energy grids depending on decarbonisation scenarios: D4.4*. [Report]. https://doi.org/10.5281/zenodo.4883664

III Persson, Urban; Möller, Bernd; Sánchez-García, Luis, & Wiechers, Eva. (2021). *District heating investment costs and allocation of local resources for EU28 in 2030 and 2050: D4.5*. [Report]. https://doi.org/10.5281/zenodo.4892271

IV Persson, Urban & Sánchez-García, Luis. (2021). *Draft recommendations for H/C outlook 2050: D2.2*. [Report]. http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-46647

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VI Persson, Urban; Atabaki, Mohammad Saeid; Sánchez-García, Luis, & Lichtenwöhrer, Peter. (2022). *H/C outlook 2050 of cities with cross-city synthesis: Deliverable D2.6 (Edited version)*. [Report]. https://doi.org/10.5281/zenodo.6524594

VII Möller, Bernd; Wiechers, Eva; Persson, Urban; Nielsen, Steffen; Werner, Sven; Connolly, David; Wilke, Ole Garcia; Sánchez-García, Luis; Moreno, Diana; Grundahl, Lars; Lund, Rasmus Søgaard; Vad Mathiesen, Brian, & Lund, Henrik. (2022). *Peta: The Pan-European Thermal Atlas: version 5.2: developed as part of the sEEnergies project*. [Dataset]. In. Flensburg: Europa-Universität Flensburg. http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-48178

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xi Möller, Bernd; Wiechers, Eva; Sánchez-García, Luis, & Persson, Urban. (2022). *Spatial models and spatial analytics results: Deliverable 5.7*. [Report]. https://doi.org/10.5281/zenodo.6524594

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XVII Sánchez-García, Luis & Persson, Urban. (2025). *Pan-European dataset of subsurface temperature isolines at 1000 m and 2000 m depth*. [Dataset]. https://doi.org/10.5281/zenodo.13799306

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Popular summary in English

Climate change is one of the greatest challenges humanity is facing, and combating it requires a radical transformation of the energy system. This transition must combine net-zero greenhouse gas emissions with energy efficiency and sustainability. From a European perspective, it would also bring the added benefit of achieving energy independence and security of supply.

The ecological transition must reach all sectors of the energy system, including the heating and cooling sector. In Europe, this sector accounts for one third of final energy demand and it is still mainly covered by fossil fuels such as coal, oil, or natural gas. To replace these polluting sources, society has a broad range of technological alternatives. First, demand could be reduced through improved building insulation. However, beyond a certain point, demand reductions become prohibitively expensive, making it necessary to also substitute fossil-based heating and cooling with lower- or zero-emission sources. Among these alternatives are individual heat pumps, biomass, and district heating and cooling networks.

District heating and cooling systems consist of a network of pipes distributing heat and/or cold from one or more production plants to end users, mainly buildings in the residential and service sectors. Like electricity grids, these networks are characterized by their ability to integrate diverse heat and cold sources over time. They can also recycle waste heat from various sources that would otherwise be completely wasted. Another key advantage of district networks is their integration with the electricity system. Thermal storage in networks is significantly cheaper than electrical storage, and linking the two sectors via combined heat and power (CHP) plants, large-scale heat pumps, and electric boilers enables the system to capitalize on this cost advantage. In this way, surplus renewable electricity can be cost-effectively stored as heat, helping the integration of higher shares of renewable energy sources such as solar and wind.

Thanks to these benefits, several European countries have prioritized district networks, and in some, they cover more than half of heating demand in the residential and service sectors. However, their average share across the European Union is much lower, around 10%. Given the advantages of district systems, their further development could significantly aid the ecological transition of the heating and cooling sector. Therefore, estimating their potential at the European level is crucial. As earlier studies have pointed out, the potential of district heating and cooling networks largely depends on the cost of the pipe infrastructure, which varies significantly depending on local conditions. Although detailed network costs can be estimated at the neighbourhood or city scale using hydraulic and structural models, applying these methods across broader regions, such as countries or the entire Europe, is not feasible due to the extensive data and computation required. Therefore, developing simplified models to estimate network costs at larger scales is essential.

District networks can also take different forms depending on parameters such as supply and return temperatures and the location of heat and cold production plants. These and other factors lead to a wide variety of network configurations, but they can generally be grouped into two main categories: warm or conventional networks and cold or ambient-temperature networks. In the former, heat is supplied at the temperature needed for space heating and domestic hot water. In the latter, heat is delivered at near-ambient temperatures, requiring end users to have heat pumps to raise the temperature to usable levels. Previous studies have argued that cold networks might be more cost-effective because they can use non-insulated pipes similar to those used for drinking water, thermal losses are negligible, and the same network can provide both heating and cooling through the bidirectional use of distributed heat pumps. However, very few studies have quantitatively compared the two configurations.

This thesis has addressed these two aspects of district heating and cooling systems. First, it investigated their potential at the European scale. As noted, this requires simplified models to estimate pipe network costs across large areas. One such model is that of Persson and Werner, which provides a first approximation of these costs. A key parameter in their model is the *effective width*, which indicates the required trench length in an area to be supplied by district heating. Previous studies had not determined reliable effective width values for all urban typologies, nor had they sufficiently accounted for the necessary connection length to individual buildings since most attention had focused on the distribution network.

This thesis carried out a detailed geographic analysis of two of the largest district heating systems in Denmark, which allowed the development of new equations for estimating *effective width*. These equations relate this parameter to urban density indicators such as the number of buildings and built area. The updated Persson & Werner model was then validated on several test areas and found to provide reasonably accurate estimates when used at aggregated levels and over large areas, but it showed limited accuracy at small scales.

Two further improvements were added to the model to account for the fact that not all buildings may be connected and that heat demand is expected to decline in the future. The enhanced model was applied to all the European Union to estimate the costs and thus the potential of district networks. One key finding is that these systems could cost-effectively meet one third of the Europe's residential and service sector heat demand by 2050.

The second part of this work examined the economic costs of warm and cold networks, both for heating only and for combined heating and cooling. This analysis is based on a detailed case study of Bilbao, which considered all key system components: heat/cold generation, distribution grid, and final-user connections. The results show that for heating-only systems, warm networks are more cost-effective due to the aggregation of demand (not all users require heat simultaneously), flexibility in energy sourcing, economies of scale in thermal storage, and lower electricity prices for industrial consumers, even when transport network costs are higher. These conclusions remain valid under varying economic conditions, including rising natural gas prices (e.g. due to the war in Ukraine) and high interest rates. However, when both heating and cooling are supplied, the costs of warm and cold networks are very similar. Warm systems require a parallel district cooling network, while cold networks do not require extra infrastructure, and the additional operating costs are minimal.

Finally, the case study focused on Bilbao also assessed how competitive district networks are compared to other low-carbon options like individual heat pumps and the predominant form of heat supply, natural gas. The comparison indicates that although both types of district networks are more cost-effective than individual heat pumps, they cannot outcompete natural gas, mainly due to the lack of a carbon pricing mechanism that would reflect its true social and environmental cost.

Populärvetenskaplig sammanfattning på svenska

Klimatförändringarna är en av de största utmaningarna mänskligheten står inför, och att hantera dem kräver en radikal omställning av energisystemet. Denna omställning måste förena nettonollutsläpp av växthusgaser med energieffektivitet och hållbarhet. Ur ett europeiskt perspektiv innebär omställningen också en fördel i form av stärkt i form av minskat importberoende av energi och stärkt försörjningstryggheoch försörjningstrygghet.

Den gröna omställningen måste nå alla delar av energisystemet – inklusive uppvärmnings- och kylasektorn. I Europa står denna sektor för cirka en tredjedel av den totala slutanvändningen av energi och är fortfarande i stor utsträckning baserad på fossila bränslen som kol, olja och naturgas. För att ersätta dessa förorenande energikällor finns det ett antal teknologiska alternativ tillgängliga. Framför allt kan efterfrågan minskas genom bättre isolering av byggnader. Men efter en viss nivå blir ytterligare renoveringar oproportionerligt dyra. Det är därför också nödvändigt att ersätta fossilbaserad uppvärmning och kylning med lågutsläpps- eller nollutsläppskällor. Bland dessa alternativ finns individuella värmepumpar, biomassa samt fjärrvärme och fjärrkyla.

Fjärrvärme och fjärrkyla består av nätverk av rör som distribuerar värme och/eller kyla från en eller flera produktionsenheter till slutanvändare – huvudsakligen byggnaderbyggnader som används för bostäder och lokaler. Precis som elnätet har dessa system fördelen att de över tid kan integrera många olika värme- och kylakällor. De kan dessutom utnyttja överskottsvärme/kyla från källor som annars skulle gå förlorade. En annan väsentlig fördel med fjärrvärme är dess samspel med elsystemet. Termisk lagring i fjärrvärmesystem är avsevärt billigare än elektrisk lagring, och kopplingen mellan sektorerna via kraftvärmeverk, stora värmepumpar och elpannor gör det möjligt att utnyttja denna kostnadsfördel. På så sätt kan överskottsel från förnybara energikällor omvandlas till värme och lagras billigt – vilket underlättar integrationen av sol- och vindenergi i det övergripande energisystemet.

Tack vare dessa fördelar har flera europeiska länder prioriterat fjärrvärme, och i vissa av dessa täcker den mer än hälften av uppvärmningsbehovet i bostads- och lokalsektorn. Den genomsnittliga andelen i Europa är dock avsevärt lägre – omkring 10%. Mot bakgrund av fjärrvärmens fördelar kan en vidareutveckling av teknologin ge ett betydande bidrag till den gröna omställningen av uppvärmnings- och kylasektorn. Det är därför avgörande att bedöma dess potential på europeisk nivå. Som tidigare studier har visat beror denna potential i hög grad på kostnaderna för rörinfrastrukturen, som varierar betydligt beroende på lokala förhållanden. Även om detaljerade nätkostnader kan uppskattas på kvarters- eller stadsdelsnivå med hjälp av hydrauliska och strukturella modeller, är det inte realistiskt att tillämpa dessa metoder på nationell eller europeisk nivå på grund av den datamängd och de beräkningar som krävs. Det är därför nödvändigt att utveckla förenklade modeller för att uppskatta nätkostnader i större skala.

Fjärrvärme kan anta olika former beroende bland annat på framlednings- och returtemperaturer samt produktionsanläggningens placering. Dessa och andra faktorer leder till olika typer av nätkonfigurationer, som i allmänhet kan delas in i två huvudtyper: Uppvärmda (konventionella) nät och tempererade nät som inte är förvärmda. I uppvärmda nät levereras värme vid den temperatur som krävs för rumsuppvärmning och tappvarmvatten. I tempererade nät levereras värmen vid en temperatur nära omgivningens, vilket innebär att slutanvändarna behöver värmepumpar för att höja temperaturen. Tidigare studier har lyft fram att tempererade nät kan vara mer konkurrenskraftiga eftersom de möjliggör användning av oisolerade rör (som för dricksvatten), eftersom värmeförlusten är minimal, samt att samma nät kan användas för både uppvärmning och kylning via tvåvägskommunikation med värmepumpar. Det finns dock få kvantitativa jämförelser mellan de två huvudtyperna.

Denna avhandling har behandlat dessa två huvudaspekter av fjärrvärme- och fjärrkylasystem och genomfört en skattning avfjärrvärmepotentialen i Europa samt beräknat kostnaderna för uppvärmda respektive tempererade nätkonfigurationer. Först analyserades potentialen för fjärrvärme på europeisk nivå. Som nämnts kräver detta förenklade modeller för att uppskatta nätkostnader över stora geografiska områden. En sådan modell har utvecklats av Persson och Werner och ger en omedelbar indikation av de förväntade kostnaderna. En nyckelparameter i deras modell är storheten effektiv bredd (eng. effective width), som anger den rörlängd som krävs i ett område för att etablera fjärrvärme. Tidigare studier har för denna parameter inte fastställt tillförlitliga värden för stadsområden med låg eller varierande befolkningstäthet och har endast i begränsad omfattning tagit hänsyn till anslutning av enskilda byggnader – fokus har främst legat på distributionsnätet.

Denna avhandling har genomfört en detaljerad geografisk analys av två av Danmarks största fjärrvärmesystem, vilket har möjliggjort utvecklingen av mer precisa metoder för att uppskatta effektiv bredd. Dessa metoder relaterar den effektiva bredden till byggnadstäthet, mätt som antal byggnader och bebyggd yta. Den uppdaterade modellen från Persson och Werner validerades därefter i flera testområden och visade sig ge rimligt noggranna uppskattningar på aggregerad nivå, men lägre precision i mindre skala.

Modellen förbättrades dessutom så att den tar hänsyn till att inte alla byggnader nödvändigtvis kommer att anslutas, samt att värmeförbrukningen förväntas minska framöver. Den uppdaterade modellen tillämpades därefter på hela EU för att uppskatta kostnader och potential för fjärrvärme. Ett centralt resultat är att sådana system på ett kostnadseffektivt sätt kan täcka en tredjedel av värmebehovet i bostads- och lokalsektorn i Europa år 2050 – och därmed utgöra en väsentlig del av vägen mot en grön omställning av den europeiska kontinenten.

Den andra delen av avhandlingen analyserade de analyserade de ekonomiska förutsättningarna för uppvärmda respektive tempererade nätkonfigurationer – både för ren uppvärmning och för kombinerad uppvärmning och kylning. Analysen är baserad på en detaljerad fallstudie av en stadsdel i den spanska staden Bilbao, där alla nyckelkomponenter i ett fjärrvärmesystem inkluderades: Värme-/kylaproduktion, distributionsnät och anslutning av slutanvändare. Resultaten visar att uppvärmda nätkonfigurationer för ren uppvärmning är mest kostnadseffektiva – dels på grund av efterfrågeaggregering (inte alla använder värme samtidigt), flexibilitet i energikällor, stordriftsfördelar vid värmelagring, samt lägre elpriser för industrikonsumenter – även när nätkostnaderna är högre. Dessa slutsatser förblir giltiga under olika ekonomiska antaganden, inklusive stigande gaspriser (till exempel som en följd av kriget i Ukraina) och höga räntor. När både uppvärmning och kylning ska levereras är däremot kostnaderna för uppvärmda och tempererade nät i stort sett likvärdiga. Uppvärmda nät kräver ett separat fjärrkylanät, medan tempererade nät inte kräver ytterligare infrastruktur, samt att deras driftskostnader är minimala.

Slutligen bedömde fallstudien av Bilbao hur konkurrenskraftiga fjärrvärmesystem är jämfört med andra lågutsläppslösningar som individuella värmepumpar och den mest utbredda uppvärmningsformen – naturgas. Jämförelsen visar att båda typerna av fjärrvärme är mer kostnadseffektiva än individuella värmepumpar, men att de inte kan konkurrera med naturgas – främst eftersom det saknas ett pris på koldioxidutsläpp som återspeglar naturgasens verkliga samhälls- och miljökostnader.

Resumé på dansk

Den grønne omstilling skal nå ud til alle dele af energisystemet – herunder også varme- og kølesektoren. I Europa står denne sektor for omkring en tredjedel af det samlede slutenergiforbrug og er fortsat overvejende baseret på fossile brændsler som kul, olie og naturgas. For at erstatte disse forurenende energikilder har samfundet adgang til en række teknologiske alternativer. Først og fremmest kan efterspørgslen reduceres gennem bedre isolering af bygninger. Men efter et vist niveau bliver yderligere renovering uforholdsmæssigt dyrt. Det er derfor også nødvendigt at erstatte fossilbaseret opvarmning og køling med lav- eller nulemissionskilder. Blandt disse alternativer er individuelle varmepumper, biomasse samt fjernvarme og -køling.

Fjernvarme og fjernkøling består af netværk af rør, som distribuerer varme og/eller kulde fra en eller flere produktionsenheder til slutbrugere – primært bygninger i bolig- og servicesektoren. Ligesom elnettet har disse systemer den fordel, at de over tid kan integrere mange forskellige varme- og kuldekilder. De kan desuden udnytte overskudsvarme og -kulde fra kilder, der ellers ville gå tabt. En anden væsentlig fordel ved fjernvarme er dens samspil med elsystemet. Termisk lagring i fjernvarmesystemer er væsentligt billigere end elektrisk lagring, og forbindelsen mellem sektorerne via kraftvarmeværker, store varmepumper og elkedler gør det muligt at udnytte denne prisfordel. På den måde kan overskudsstrøm fra vedvarende energikilder omdannes til varme og lagres billigt – hvilket understøtter integrationen af sol- og vindenergi i det samlede energisystem.

Takket være disse fordele har flere europæiske lande prioriteret fjernvarme, og i nogle dækker den over halvdelen af varmebehovet i bolig- og servicesektoren. Den gennemsnitlige andel i Europa er dog væsentligt lavere – omkring 10%. I lyset af fjernvarmens fordele kunne en videreudvikling af teknologien yde et markant bidrag til den grønne omstilling af varme- og kølesektoren. Det er derfor afgørende at vurdere dens potentiale på europæisk niveau. Som tidligere studier har påpeget, afhænger dette potentiale i høj grad af omkostningerne ved rørinfrastrukturen, som varierer betydeligt afhængigt af lokale forhold. Selvom detaljerede netomkostninger kan estimeres på kvarters- eller byniveau ved hjælp af hydrauliske og strukturelle modeller, er det ikke realistisk at anvende disse metoder på nationalt eller europæisk plan på grund af datamængden og de beregninger, der kræves. Det er derfor nødvendigt at udvikle forenklede modeller til estimering af netomkostninger i større skala.

Fjernvarme kan antage forskellige former afhængigt af blandt andet fremløbs- og returløbstemperaturer samt placeringen af produktionsanlæg. Disse og andre faktorer fører til forskellige typer netkonfigurationer, som generelt kan opdeles i to hovedtyper: Opvarmede (konventionelle) net og tempererede net, der ikke opvarmes. I opvarmede net leveres varme ved den temperatur, der er nødvendig til rumopvarmning og varmt brugsvand. I tempererede net leveres varmen ved en temperatur tæt på omgivelsernes, og slutbrugerne har derfor behov for varmepumper til at hæve temperaturen. Tidligere studier har fremhævet, at tempererede net kan være mere konkurrencedygtige, fordi de muliggør brug af uisolerede rør (som dem til drikkevand), da varmetabet er minimalt, og fordi det samme net kan anvendes til både opvarmning og køling gennem tovejskommunikation med varmepumper. Der findes dog kun få kvantitative sammenligninger mellem de to hovedtyper.

Denne afhandling har behandlet disse to hovedaspekter af fjernvarme- og kølesystemer: Fjernvarmepotentialet i Europa og omkostningerne ved henholdsvis opvarmede og tempererede netkonfigurationer. Først er potentialet for fjernvarme på europæisk niveau blevet analyseret. Som nævnt kræver dette forenklede modeller til at estimere netomkostninger over store geografiske områder. En sådan model er udviklet af Persson og Werner og giver en umiddelbar indikation af de forventede omkostninger. Et nøgleparameter i deres model er den såkaldte *effective width*, som angiver den nødvendige rørlængde i et område for at etablere fjernvarme. Tidligere studier har ikke fastlagt pålidelige værdier for byområder med varierende befolkningstæthed og har i begrænset omfang taget højde for tilslutningen til de enkelte bygninger – fokus har hovedsageligt været på distributionsnettet.

Denne afhandling har gennemført en detaljeret geografisk analyse af to af Danmarks største fjernvarmesystemer, hvilket har muliggjort udviklingen af mere præcise metoder til at estimere *effective width*. Disse metoder relaterer textiteffective width til bygningstætheden, målt som antal bygninger og bebygget areal. Den opdaterede model fra Persson og Werner blev derefter valideret i flere testområder og viste sig at give rimeligt nøjagtige estimater på aggregeret niveau, men lavere præcision i mindre skala.

Modellen blev desuden forbedret, så den tager højde for, at ikke alle bygninger nødvendigvis bliver tilsluttet, samt at varmeforbruget forventes at falde fremover. Den opdaterede model blev derefter anvendt på hele EU til at estimere omkostninger og potentiale for fjernvarme. Et centralt resultat er, at sådanne systemer omkostningseffektivt kan dække en tredjedel af varmebehovet i bolig- og servicesektoren i Europa i 2050, og dermed udgøre en væsentlig del af vejen mod en grøn omstilling af det europæiske kontinent.

Anden del af afhandlingen analyserede de økonomiske omkostninger ved henholdsvis opvarmede og tempererede netkonfigurationer, både til ren opvarmning og til kombineret opvarmning og køling. Analysen er baseret på et detaljeret casestudie af Bilbao, hvor alle nøglekomponenter i et fjernvarmesystem blev inddraget: Varme-/køleproduktion, distributionsnet og tilslutning af slutbrugere. Resultaterne viser, at opvarmede netkonfigurationer til ren opvarmning er mest omkostningseffektive, dels på grund af efterspørgselsaggregering (ikke alle bruger varme samtidigt), fleksibilitet i energikilder, stordriftsfordele ved varmelagring og lavere elpriser for industriforbrugere, selv når netværksomkostningerne er højere. Disse konklusioner forbliver gyldige under forskellige økonomiske forudsætninger, herunder stigende gaspriser (eksempelvis som følge af krigen i Ukraine) og høje renter. Når både opvarmning og køling skal leveres, er omkostningerne ved opvarmede og tempererede net derimod stort set ens. Opvarmede net kræver et separat fjernkølingsnet, mens tempererede net ikke kræver yderligere infrastruktur, og deres driftsomkostninger er minimale.

Endelig vurderede casestudiet af Bilbao, hvor konkurrencedygtige fjernvarmesystemer er sammenlignet med andre lavemissionsløsninger som individuelle varmepumper og den mest udbredte opvarmningsform – naturgas. Sammenligningen viser, at begge typer fjernvarme er mere omkostningseffektive end individuelle varmepumper, men at de ikke kan konkurrere med naturgas, primært fordi der mangler en pris på CO_2-udledning, som afspejler naturgassens reelle samfunds- og miljøomkostninger.

Resumen en castellano

El cambio climático es uno de los principales desafíos que afronta la humanidad y la lucha contra el mismo requiere una transformación radical del sistema energético. Esta transición ha de aunar unas emisiones de gases de efecto invernadero netas nulas con la eficiencia energética y la sostenibilidad. Además, desde una perspectiva europea, la lucha contra el cambio climático tendría el beneficio adicional de lograr la independencia energética y la seguridad de suministro.

La transición ecológica debe afectar a todos los sectores del sistema energético, incluido el sector de la climatización. En Europa, este sector supone un tercio de la demanda final de la energía; dicha demanda aún está cubierta principalmente por combustibles fósiles como el carbón, el petróleo o el gas natural. Para sustituir estas fuentes de energía contaminantes la sociedad tiene a su disposición una amplia gama de opciones. En primer lugar, podría reducirse la demanda final mediante la mejora del aislamiento térmico de los edificios. No obstante, las reducciones de la demanda más allá de cierto punto resultan prohibitivas, por lo que también se hace necesario sustituir las fuentes de calor y frío fósiles por otras con emisiones menores o nulas. Entre las diferentes opciones tecnológicas a las que se podría recurrir, se encuentran las bombas de calor individuales, la biomasa o las redes de calor y frío.

Las redes de calor y frío, también conocidas como sistemas de calefacción urbana o calefacción a distancia, están formadas por una red de tuberías que distribuyen el calor y el frío desde una o varias plantas de producción hasta los consumidores finales, principalmente edificios en los sectores residencial y de servicios. Al igual que otras redes como la eléctrica, las redes de calor se caracterizan por su capacidad para integrar diferentes fuentes de calor y frío a lo largo del tiempo. Además, estos sistemas permiten aprovechar el calor residual proveniente de múltiples fuentes, que de otra forma sería completamente desperdiciado. Otra ventaja de las redes de calor y frío para el sistema energético en su conjunto deriva de su integración con el sistema eléctrico. El almacenamiento térmico en redes resulta mucho más económico que el almacenamiento eléctrico y la conexión de los dos sectores a través de centrales de cogeneración, grandes bombas de calor y calderas eléctricas, permite aprovechar esta ventaja económica. Así, los excedentes de producción renovables pueden

almacenarse en forma de calor, permitiendo de este modo incrementar la penetración de fuentes renovables como la solar o la eólica.

Gracias a estas ventajas, algunos países europeos apostaron por desarrollar su uso y en varios cubren más de la mitad de la demanda de calor en los sectores residencial y servicios. Sin embargo, en el conjunto de la Unión Europea su aportación media es mucho menor, tan sólo del 10%. Dadas las ventajas de las redes de calor y frío mencionadas previamente, su desarrollo en Europa más allá de su expansión actual podría facilitar la transición ecológica del sector de la climatización. Por lo tanto, la estimación de su potencial a nivel europeo tiene una importancia primordial. Tal y como han señalado estudios anteriores, el potencial de las redes de calor y frío depende fundamentalmente de los costes de las redes de tuberías y éstos varían significativamente de un lugar a otro en función de las características locales. Aunque estos costes pueden determinarse fácilmente en barrios o ciudades enteras gracias al uso de modelos hidráulicos y estructurales, su aplicación en zonas más extensas (regiones, países o toda Europa), no resulta viable dado el gran número de cálculos y la gran cantidad de información precisada. Por consiguiente, el desarrollo de modelos sencillos que permitan obtener una estimación de los costes de redes en aplicaciones a gran escala resulta primordial.

Por otra parte, las redes de calor y frío pueden adoptar configuraciones diversas en función de varios parámetros como las temperaturas de impulsión y retorno o la ubicación de las plantas de producción de calor y frío. La combinación de estos y otros parámetros resulta en múltiples tipos de redes, pero que pueden clasificarse en dos grandes categorías: las redes de temperatura elevada y las redes de temperatura ambiente. Por un lado, en las redes de alta temperatura o convencionales, las plantas de producción suministran todo el calor a la temperatura que necesitan los consumidores para la calefacción y la producción de agua caliente sanitaria. Por otro lado, las redes de baja temperatura distribuyen calor a temperaturas próximas a la temperatura ambiente y es necesario que los consumidores dispongan de bombas de calor capaces de elevar la temperatura hasta el nivel requerido. Estudios anteriores han defendido que las redes de temperatura ambiente podrían ser más económicas, ya que las redes podrían construirse con tuberías sin aislamiento iguales a las empleadas en redes de agua potable, las pérdidas de calor serían inapreciables y sería factible aprovechar la misma red para suministrar tanto calor como frío gracias al doble uso de las bombas de calor distribuidas. No obstante, hay muy pocos estudios que hayan comparado cuantitativamente los dos tipos de redes.

Esta tesis ha tenido como objetivo abordar estos dos aspectos de las redes de calor y frío. En primer lugar, se ha investigado su potencial a nivel europeo. Tal y como se ha mencionado previamente, para lograr esta meta hace falta disponer de modelos sencillos que permitan calcular los costes de las redes en áreas extensas. Una de las herramientas desarrolladas con este fin es el modelo de Persson y Werner, que ofrece una primera aproximación a estos costes. Este modelo cuenta con varios parámetros entre los que se encuentra la *anchura efectiva*, *effective width* en inglés, que proporciona la longitud de zanja necesaria en una zona en la que se vaya a implantar una red. Desgraciadamente, estudios previos no habían logrado identificar los valores de la *anchura efectiva* en todos los tipos de zonas urbanas. Además, tampoco se había prestado suficiente atención a la longitud necesaria de las acometidas a cada edificio, ya que toda la atención se había centrado en la red de distribución.

En esta tesis se ha efectuado un análisis geográfico detallado de dos de las redes de calor más extensas de Dinamarca, gracias al cual se han podido obtener nuevas ecuaciones para la *anchura efectiva*. En dichas ecuaciones se relaciona la *anchura efectiva* con varios indicadores de densidad urbana como el número de edificios y la superficie construida. Posteriormente se ha aplicado el modelo de Persson & Werner, con las nuevas ecuaciones, a varias zonas con el fin de validarlo y se ha podido determinar que el modelo proporciona estimaciones relativamente precisas cuando se emplea a nivel agregado y en zonas de elevada extensión, pero que su precisión deja que desear cuando se utiliza en zonas pequeñas.

Al modelo se le añadieron posteriormente dos mejoras con el fin de tener en cuenta el hecho de que probablemente no todos los edificios se conecten a la red y que las demandas de calor disminuirán indudablemente en el futuro. Una vez mejorado, se aplicó el modelo de Persson y Werner a todos los países de la Unión Europea (UE-27), con el objeto de estimar los costes de las redes de calor y así su potencial. Uno de los hallazgos de este estudio es que estos sistemas podrían proveer un tercio de la demanda europea de calor en los sectores residencial y de servicios para 2050.

En segundo lugar, este trabajo ha examinado los costes económicos de las redes de temperatura elevada y ambiente, tanto para el suministro único de calor, como para el suministro conjunto de calor y frío. Este examen se ha llevado a cabo por medio de un estudio detallado de la ciudad de Bilbao, en el que se han tenido en cuenta todos los elementos que conforman un sistema de climatización urbana: producción de calor y frío, transporte y conexiones con los consumidores finales. Los resultados de esta investigación muestran que, para el suministro exclusivo de calor, las redes de temperatura elevada serían más económicas que las redes de temperatura ambiente gracias a la simultaneidad de consumos (no todos los consumidores demandan calor al mismo tiempo, por lo que la central de producción tan solo tiene que proveer el consumo agregado), la posibilidad de combinar múltiples fuentes de energía, la economía del almacenamiento térmico a gran escala y los menores precios de la electricidad para consumidores industriales. Estos costes totales más bajos se producen incluso a pesar de los mayores costes de la red de transporte. Además, estos hallazgos son sólidos ante una serie de cambios en las condiciones económicas entre las que se encuentran la subida drástica de precios del gas natural a raíz de la guerra de Ucrania o unos tipos de interés elevados. Sin embargo, cuando las redes han de suministrar los dos tipos de servicios, frío y calor, los costes son muy similares. Mientras que en la red de temperatura elevada es preciso construir una red de frío paralela a la de calor, en la red de temperatura ambiente no es necesario realizar ninguna inversión y los costes de operación adicionales son muy reducidos.

Finalmente, el estudio centrado en Bilbao también evaluó la competitividad de las redes de calor con otras fuentes bajas en carbono como las bombas de calor individuales y la principal fuente de calor en la actualidad, el gas natural. Esta comparación indica que, si bien los dos tipos de redes de calor serían más económicos que las bombas de calor individuales, no lograrían desbancar al gas natural, dado que la imposición sobre el mismo es prácticamente nula, lo que no permite que los consumidores tengan en cuenta el coste social de las emisiones de carbono.

Chapter 1

Introduction

> Coal in truth stands not beside but entirely above all other commodities. It is the material energy of the country —the universal aid—the factor in everything we do. With coal, almost any feat is possible or easy; without it, we are thrown back into the laborious poverty of early times.
>
> *William Stanley Jevons*
> *The Coal Question, 1866, page 2*

Abundant and inexpensive energy has been the *condicio sine qua non* for the radical change in wellbeing that mankind has experienced over the last three centuries since the dawn of the Industrial Revolution. As illustrated in Figure 1.1, between 1820 and the present date a nearly fourfold increase in per capita energy demand and a thirty-fold increment of the total energy demand have taken place. This incredible growth of available energy not only has enabled the human species to multiply but also to overcome the preterite Malthusian trap [1], that condemned the majority of the population to abject levels of material poverty [2]. Between 1820 and 2016 global mean income levels rose from merely 1 174 2011-US$ to 14 700 2011-US$ (Bolt & van Zanden, 2021, page 44), extreme poverty fell from four fifths of the population to a tenth (Moatsos, 2021, page 195) and life expectancy has improved by 40 years, reaching 70 years (Riley, 2005).

[1] An interesting summary of Malthus work (Malthus, 1798) is provided by Roser (2020) in Our World in Data.

[2] It has been estimated that in 1820 886,8 out of a world population of 1 057 million (83,9%) lived in extreme poverty (Bourguignon & Morrisson, 2002).

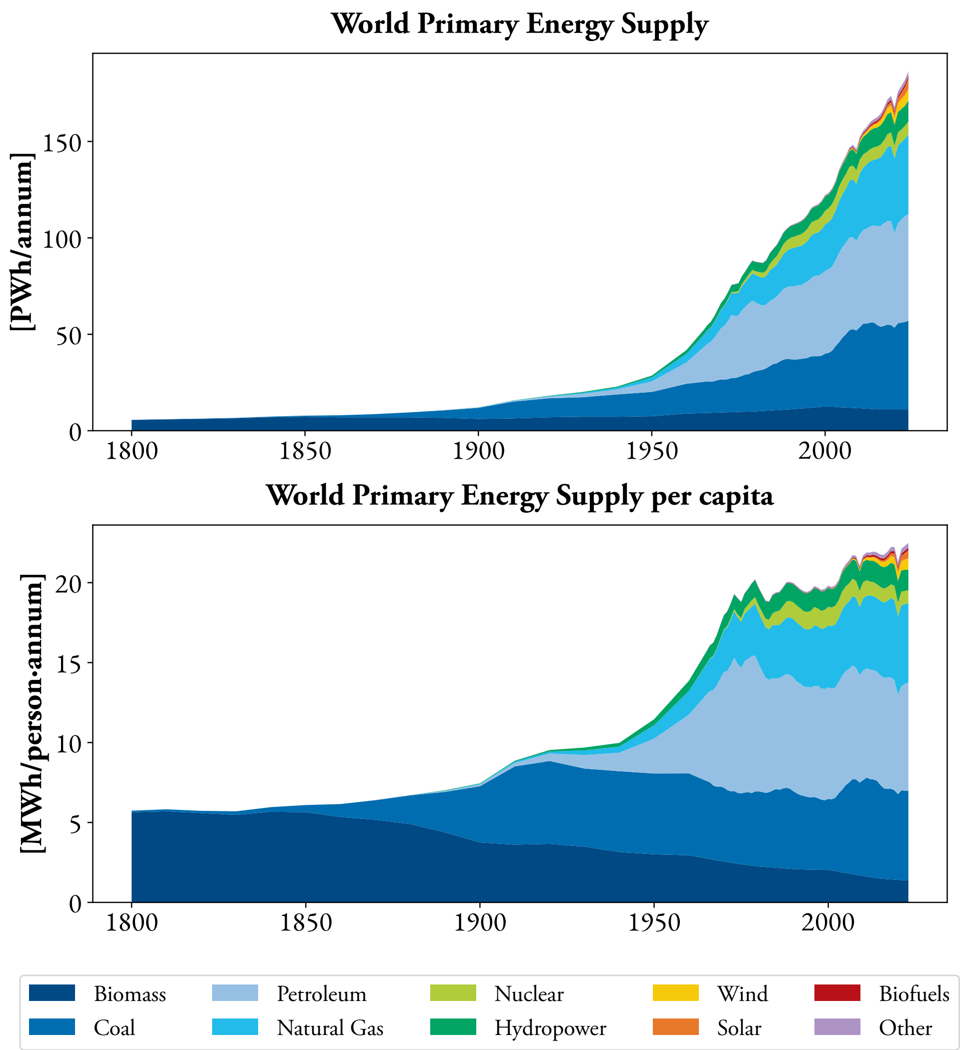

Figure 1.1: World Primary Energy Mix [3]. Various sources [4].

This energy cornucopia has been delivered by fossil fuels, the remnants of ancient organisms that captured solar energy aeons ago and stored it as chemical bonds. However, the bounty

[3] The primary energy of non-fossil sources is corrected to the inputs that would be needed if it were generated from fossil fuels. This "*substitution method*", assumes that wind and solar electricity are as inefficient as coal or gas.

[4] World primary energy data have been retrieved from Ritchie et al. (2025), whose dataset is based on information gathered by Smil (2016) and Dale (2021). World Population data were downloaded from Roser et al. (2013), which, in turn, were based on data from Gapminder (2022) and United Nations - Department of Economic and Social Affairs - Population Division (2022).

of cheap fossil fuels is bound to come to an end. All fossil energy sources, which provide over four-fifths of the world's primary energy demand (Ritchie et al., 2022), are probably near the culmen of their production volumes, or peak, after which they will experience a decline. Petroleum, which is the world's most used energy source, accounting for roughly a third of the world's primary energy demand, and essential in sectors such as transport or agriculture, shows signs of having reached its peak production; conventional sources have plateaued since the turn of the century (Al-Fattah, 2020; Wachtmeister & Höök, 2020; Laherrère et al., 2022) and the remainder has been covered by unconventional resources. Coal, the second source of primary energy, has a more uncertain outlook due to the large reserves; studies provide different estimates ranging from the last decade [5] (Rutledge, 2011) to the forthcoming decades (Mohr & Evans, 2009; Höök et al., 2010).

Simultaneously, the burning of fossil fuels over the last two centuries has drastically increased the concentration of carbon dioxide in the atmosphere as illustrated in Figure 1.2, which together with other gases has led to global warming. This climate change menaces the Earth's ecosystems and puts humanity's mankind's future in peril. The United Nations' Nations' Intergovernmental Panel on Climate Change (IPCC) has extensively documented the impacts that carbon emissions have on the Earth and its dwellers, including increases in the frequency and severity of extreme weather events such as droughts or heavy precipitation events, the endangerment of coastal areas due to sea level rise, the reduction of water availability for agriculture production or the deterioration of ecosystems key for food production (Pörtner et al., 2022).

First, the rise in temperatures has a direct impact on human life as human exposure to high temperatures is associated with morbidity and an elevated risk of premature death (Gasparrini et al., 2015). Vicedo-Cabrera et al. (2021) find that find that 37,0% of warm-season heat-related deaths during the period 1991-2018 can be attributed to anthropogenic climate change and this burden is bound to increase as temperatures continue to rise. This temperature increase would also pave the way for the spread of mosquito-borne diseases such as malaria or dengue to new areas of the globe (Bouzid et al., 2014; Caminade et al., 2014; Colón-González et al., 2021).

Global warming has also contributed to mean and extreme sea levels rise due to ocean thermal expansion and melting of glaciers and ocean acidification, among others, according to Wong et al. (2014). These effects of climate change will likely contribute to the decline of the extent of seagrasses and kelps in the temperate zone, or to mass coral bleaching and mortality (Wong et al., 2014), which would have cascading impacts as these ecosystems provide habitats and food for a diversity of marine life. In addition, the endangerment of coastal areas due to flooding and more frequent storms could not only affect human life

[5] Rutledge (2011) does not provide a date for the production peak, but based on his logistic regressions, it can be estimated to occur around 2015.

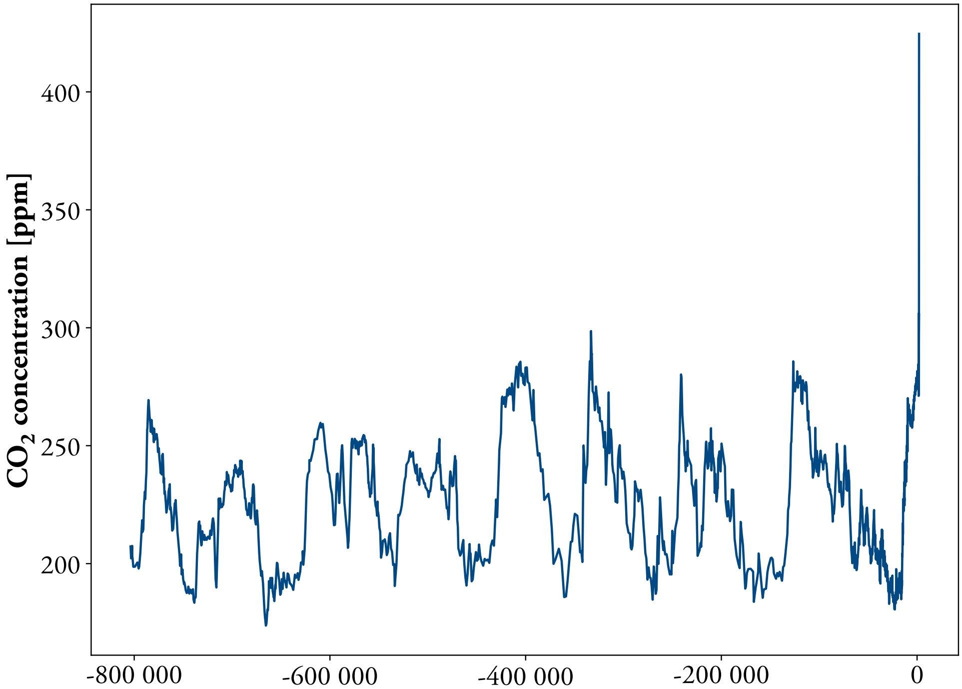

Figure 1.2: Concentration of Carbon Dioxide in the Atmosphere (parts per million). Sources: (National Oceanic and Atmospheric Administration (NOAA), 2025a, 2025b)

but also wreak havoc on the economy, with impacts on infrastructure (Wong et al., 2014) and economic activities such as tourism (Toimil-Silva et al., 2018) or fisheries.

Climate change would also affect precipitations, but this impact is very geographically heterogeneous. For instance, in most of Europe mean and heavy precipitations will likely increase whereas in Southern Europe mean precipitations will likely dwindle and drought periods will probably be more common (Bednar-Friedl et al., 2022). Due to these effects and the increase of plants evapotranspiration needs, substantial agricultural yield losses have been projected for most European areas over the 21st century. In addition, the increase of heavy precipitations would lead to higher risks of flooding events.

Until now most effects of climate change have been proportional to recent temperature changes, which in turn are proportional to the cumulative emissions. However, the Earth's ecosystems could undergo massive and sudden shifts when certain thresholds, tipping point, are exceeded (Arias et al., 2021, Box TS.9: pages 106-107; Cobb et al., 2021, section 1.4.4.3: pages 202-203). One of these tipping points is permafrost thaw, which could release immense amounts of greenhouse gases currently stored underground (Costa et al., 2021, section 5.4.9.1.2: page 740). Another tipping point would occur if the Atlantic Meridional

Overturning Circulation (AMOC) were to slow-down or collapse. The slow-down of AMOC could destabilize or disrupt the East Asian and the West African monsoons, causing drought in Africa's Sahel region and the Amazon and trigger a heat build up in the Southern Ocean, which could accelerate Antarctic ice loss (Lenton et al., 2019). In Northern Europe, a collapse of the AMOC could drive temperatures down, even as the rest of the world continues to warm, which could make some areas of Scandinavia inhabitable (Rahmstorf, 2024).

In summary, the drastic rise in energy use has made possible the unprecedented levels of material well-being that humanity has reached. Unfortunately, this increase has been chiefly based on exhaustible fossil fuels, whose combustion has also triggered a change in the global climate with potentially catastrophic consequences.

1.1 Motivation

In Europe, greenhouse gas emissions [6] mainly stem from the energy sector, accounting for roughly three quarters, followed by industrial processes and agriculture [7], each responsible for a tenth of total emissions [8] and waste management with barely 3% (European Commission, 2025c). Emissions in the energy sector are driven by the burning of fossil fuels, which in 2023 still accounted for 68,7% of the primary [9] energy supply (European Commission, 2023b). Therefore, tackling climate change calls for a drastic reduction of fossil fuel use.

One of the areas target for decarbonisation is the heating and cooling sector, which similarly to the overall energy sector, is still dominated by fossil fuels such as natural gas, petroleum or coal. As of 2015-2017, the direct combustion of these energy sources represented 64% of the useful heating demand in the residential and service sectors (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al., 2017; Mandel et al., 2022). For abandoning these sources, society has an array of measures, energy sources and technologies at its disposal. Firstly, heating and cooling demands could be reduced through improved thermal properties of buildings. This measure tends to be economic when implemented with other

[6] Including carbon dioxide and other gases with warming potential such as methane.

[7] Emissions in the agriculture sector do not refer to the energy use but rather enteric fermentation, manure management, rice cultivation, burning of savannas and residues, liming, and fertilizer application.

[8] Land use, land use change, and forestry (LULUCF) have a negative contribution to total emissions, i.e., they represent a net sink, and they have been disregarded in this calculation. Therefore, total emissions do not represent the overall net emissions including both sinks and sources but just gross total emissions.

[9] This share has been calculated as the ratio between fossil energy [FE] and total energy [Total] for the UE-27. Note though that this figure is somewhat misleading as the conversion of fossil fuels into useful energy (e.g. electricity) typically entails substantial losses, whereas hydro, wind, solar photovoltaic, tide, wave and ocean energies directly deliver electricity. Were those sources to be the output of power plants with a mean efficiency of 40%, the share of fossil fuels would fall to 62,4% and the share of renewables would increase from 19,5% to 26,9%.

renovation works, but beyond a certain point, additional reductions of the heat demand become prohibitively expensive. Secondly, society could embrace low-carbon heating and cooling sources, such as individual heat pumps, biomass, geothermal, solar thermal or residual heat from other activities. These heating and cooling sources may deliver heat or cold *in situ* at the consumers' premises or be used centrally and the heat or cold distributed through a district heating network.

District heating and cooling networks are an infrastructure that enables the recovery of heat that would otherwise be wasted and the integration of various energy sources whose individual use on a building level would not be cost-effective (Frederiksen & Werner, 2013a). Furthermore, these systems, when coupled with the electricity sector through combined heat and power plants and power-to-heat installations, can pave the way for the integration of higher shares of intermittent renewable energy sources in the electricity sector. Thanks to these and other advantages district heating and cooling systems could contribute to reaching a decarbonised Europe more cost-effectively and attaining an energy system more flexible, resilient and prepared for the future.

However, district heating and cooling systems currently meets a minor fraction of the European heating and cooling supply despite having reached substantial shares in some European countries. This modest penetration begs the question of whether district energy could assist the decarbonisation efforts further and become a central element of the continent's heating and cooling provision.

Furthermore, district heating and cooling networks may adopt different arrangements in terms of temperature levels and heating and cooling production location, which leads to a further question. If district heating and cooling networks are to gain prominence, what kind of configuration could deliver the most benefits and under what circumstances?

1.2 Objective

The overarching objective of the research leading to this thesis has been to contribute to the body of knowledge on district heating that could facilitate the transition to a carbon-neutral society. Within this broad scope, two knowledge gaps were identified.

The first knowledge gap revolves around the potential for district heating systems in the future European heating and cooling supply. As prior research has shown, the possibility of a cost-effective deployment of district heating systems is highly dependent on network costs. These investment expenditures can be evaluated by performing detailed hydraulic and static calculations in small-scale appraisals. However, regional, national or continental assessments demand much more straightforward estimation methods such as the network capital cost model developed by Persson & Werner. Unfortunately, some of the model parameters have not been sufficiently studied, and the model has never been validated.

Furthermore, prior assessments of continental district heating feasibility have been based on simpler versions of the model that did not take into consideration all elements of a district heating network.

The second knowledge gap involves network configurations. Researchers have identified a substantial number of possible combinations of network temperatures, number of pipes, and heating and cooling production location. A great deal has been written, and passionate arguments have been held on the nomenclature and the qualitative benefits of the various settings. Nonetheless, few techno-economic assessments have been run.

Based on these identified research gaps, this inquiry has aimed to address the following goals:

- Improve the district network cost developed by Persson & Werner and validate it.
- Apply the enhanced Persson & Werner model to the entire European continent in order to study the potential for district heating networks.
- Analyse the economic costs and benefits of various district heating and cooling network configurations.

1.3 Thesis Outline

Chapter 2: The current energy outlook in Europe reviews the energy situation in Europe, with special emphasis on the heating and cooling sector and the available options for decarbonisation.

Chapter 3: District heating and cooling describes the main features of district heating and cooling technology, its evolution over the last 150 years, as well as its potential benefits for the decarbonisation of the heating and cooling supply.

Chaper 4: Network costs presents the research problem concerning the cost modelling of district heating and cooling networks. A brief introduction to the topic is followed by a summary of the applied methodology, results, a discussion of the results with special care to their limitations and concluding remarks.

Chapter 5: Network configurations delves into the matter of district heating and cooling configurations, that is, the combination of temperatures and production location. The chapter begins with an overview of the various settings and a discussion of their benefits and drawbacks according to previous literature. This critique is followed by a presentation of the specific research problem, a summary of the methods and results, an in-depth discussion on their limitations and implications, and is finished with short concluding remarks.

Chapter 6: Concluding remarks summarises the thesis contributions to the body of district heating research.

Chapter 7: Future research suggests potential lines of work expanding the research presented in this thesis, as well as other topics.

Chapter 2

The current energy outlook in Europe

The European Union [10] has made significant progress in the last two decades in increasing the share of low-carbon energy sources in its energy mix [11]. Between the eve of the new millennium and 2024, the share of renewable energy sources has risen from less than 10% of the gross final energy consumption to nearly a quarter (European Commission, 2024b). In the electricity sub-sector, the evolution has been even more impressive and renewable energy sources reached 44% of the electricity production [12] in 2023 (European Commission, 2025g).

Notwithstanding this positive development, the overall energy context in Europe is still characterised by the predominance of fossil fuels. This reliance on fossil fuels not only

[10] The European Union refers to the EU-27, excluding the United Kingdom unless otherwise specified.

[11] Including renewable energy sources and nuclear.

[12] The share has been calculated as the ratio between renewables and biofuels [RA000] and the total production [TOTAL].

[13] Difference between imports and exports. It includes the following energy products: 2701 - Coal; briquettes, ovoids and similar solid fuels manufactured from coal; 2702 - Lignite, whether or not agglomerated (excluding jet); 2703 - Peat, including peat litter, whether or not agglomerated; 2704 - Coke and semi-coke of coal, of lignite or of peat, whether or not agglomerated, retort carbon; 27090090 - Petroleum oils and oils obtained from bituminous minerals, crude (excluding natural gas condensates); 27111100 - Natural gas, liquefied; 27112100 - Natural gas in gaseous state; 27090010 - Natural gas condensates. These products have been selected following Eurostat (2025) and it must be noted that they exclude electricity, uranium and biomass. Nonetheless, electrical energy (Combined Nomenclature code 2716), has a deficit amounting a few million per month; biomass (Combined Nomenclature codes 4401 and 4403 according to Alakangas et al. (2011)), accounts for a minimal deficit of circa 100 million € per month and uranium (Combined Nomenclature codes 284410, 284420 and 840130 according to Lapenko et al. (2025)) alternates between a deficit and a surplus of a few millions per month. Additionally, this selection differs from the set used in the dataset published by Eurostat on the net trade balance of energy products (European Commission, 2025d).

entails a heavy burden on the European economy but also poses a threat to energy security.

Figures 2.1 and 2.2 illustrate the two different aspects of this problem. On one side, Figure 2.1 depicts the energy dependence across Europe, showing that all European countries but Norway are net energy importers. For the European Union, approximately 70% of the

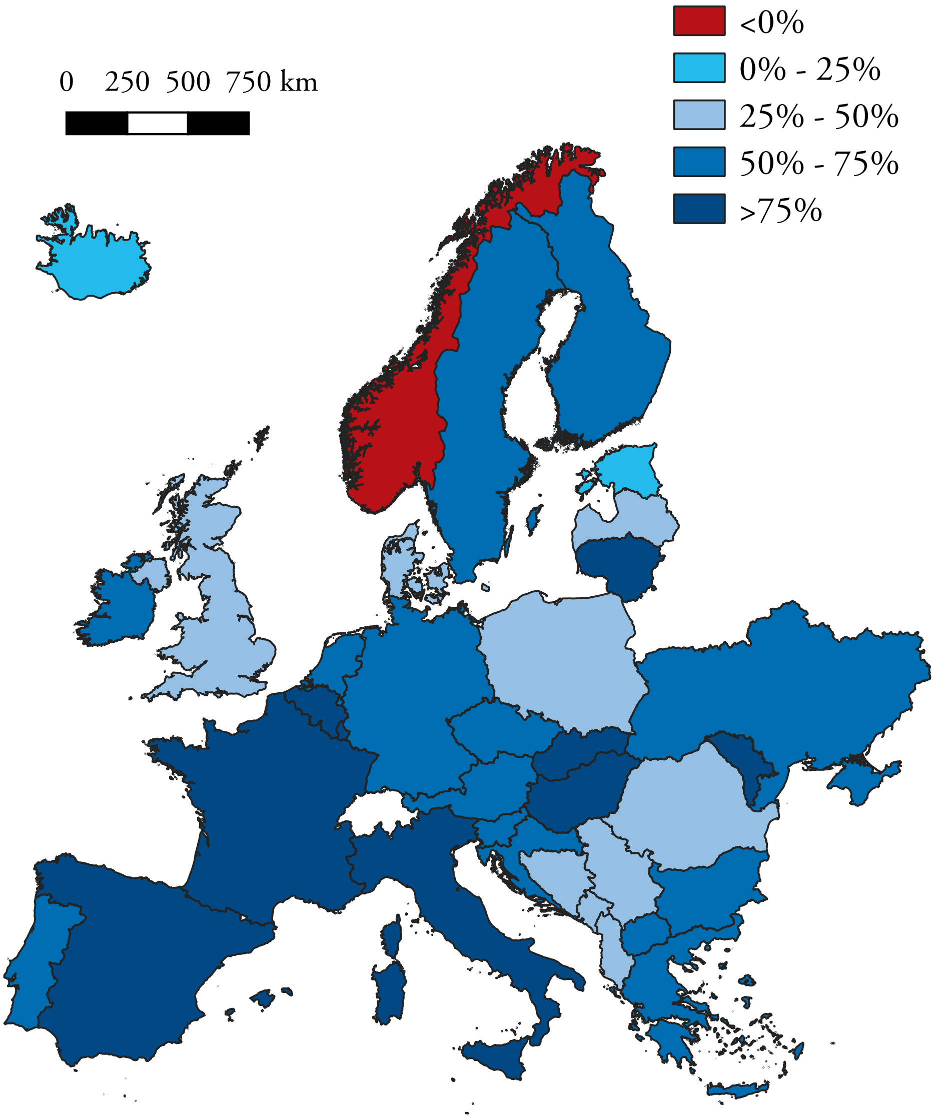

Figure 2.1: Primary energy dependence in Europe. Sources: Own elaboration based on European Commission (2023b).

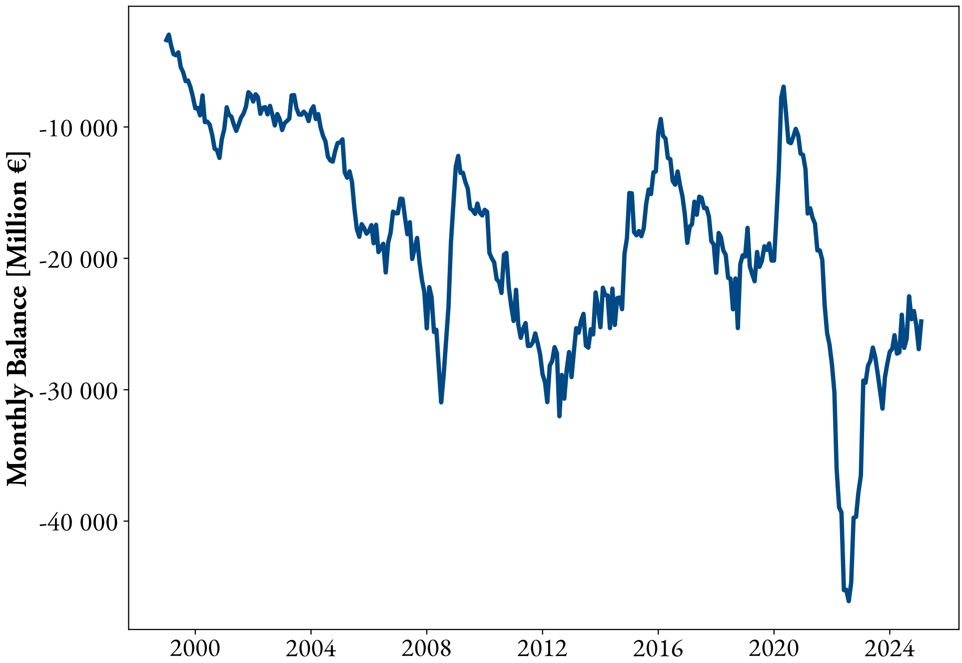

Figure 2.2: Monthly trade energy balance [13]. Sources: Own elaboration based on European Commission (2022).

gross available energy is imported (European Commission, 2023b), and this dependence has varied very little over the last three decades[14]. On the other side, Figure 2.2 portrays the economic toll on the European economy, which has generally deteriorated over time. For instance, the net import of fossil fuels accounted for nearly 600 000 million euros or 3,7% of the European Gross Domestic Product [15] in 2022 (European Commission, 2025j).

As hinted in Figure 2.2, the invasion of Ukraine by Russia triggered the worst Energy Crisis that Europe has experienced since the Oil Crises of the 1970s. Gas prices soared in the European markets [16] [17] after Russian deliveries of natural gas plummeted and had to be

[14]The dependence ratio has been calculated as the ratio between the difference of imports and exports, and the gross available energy. Unlike Eurostat or the International Energy Agency, nuclear heat has been considered among the imports since Europe's uranium production is negligible (Euroatom Supply Agency, 2022)

[15]The EU-27 GDP amounted 16 144 069 million €.

[16]The volume-weighted annual average price in the Dutch TTF increased from 15,8 €/MWh to 153,2 €/MWh between 2019 and 2022 (investing, 2023). Moreover, the average import prices, as declared in the European customs, rose in a similar fashion from 2019 averages of 22,9 €/MWh and 26,8 €/MWh for gaseous and liquefied natural gas, respectively, to all-time highs of 122,0 €/MWh and 146,0 €/MWh in 2022 (European Commission, 2022).

[17] Prices and energy volumes have been calculated based on mass flows as reported by Eurostat's commerce

substituted by imports of liquefied natural gas [18]. This dramatic rise in natural gas prices also brought about considerable increases in electricity prices due to the marginal nature of electricity spot markets [19].

In this context of energy dependence, market instability and desire to decarbonise Europe, the European Commission and the Council of the European Union launched the European Green deal in 2019 (European Commission, 2019a), *"a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use".* The European Green Deal constituted an initial and general roadmap of key policies and measures to tackle climate change, while ensuring the economic prosperity of the continent.

Later, the Commission presented in July 2021, the "Fit for 55" package, a set of concrete measures aimed at delivering the goals of the European Green Deal (European Commission, 2021a). These measures included among others, a reform of the European Trading System, an extension to the buildings and transport sector (European Commission, 2023a), a reform of the framework of energy taxation, so it is aligned with the Union's climate goals (European Commission, 2021b), a Carbon Border Adjustment Mechanism (European Commission, 2021c), conceived to prevent "carbon leakage", i.e. the exit of carbon intensive industries to more lax regulatory environments (Morsdorf, 2022; Bellora & Fontagné, 2023), and a Social Climate Fund (European Commission, 2021d) destined to ameliorate the burden of fossil price increases in vulnerable households.

After the due *trilogue* between the European Commission, the Council of the European Union and the European Parliament, Commission President Ursula von der Leyen announced the completion of the ensemble of actions in 2023 (European Commission, 2023a).

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statistics and the Net Calorific Values provided by Eurostat's guidelines on Energy Balances (European Commission, 2019b). These guidelines refer to a European Regulation on monitoring and reporting of greenhouse gas emissions (European Commission, 2018b), which, in turn, takes its values from the IPPC guidelines on National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change (IPCC), 2006). These latter guidelines suggest Net Calorific Values of 44,2 GJ/ton and 48 GJ/ton for liquefied and gaseous natural gas, respectively.

[18] Natural Gas imports from Russia dropped from 516,4 TWh in 2021 to 152,4 TWh in 2023 (European Commission, 2022)

[19] As an example, spot prices in the Iberian Market rose from a 2019 yearly average of 48 €/MWh to 168 €/MWh in 2022 (Operador del Mercado Ibérico de Energía - Polo Español (OMIE), 2025); similarly, prices in the highly integrated Danish market grew from around 40 €/MWh to nearly 220 €/MWh (Energinet, 2025a). Note that in both cases, the prices represent simple arithmetic means without taking into consideration energy volumes.

2.1 The heating and cooling sector

This section provides a brief overview over the heating and cooling sector with special emphasis on the drivers of energy use and the energy sources currently used to meet it.

2.1.1 Energy use

The heating and cooling sector accounted for approximately half of the final energy demand[20] of the European Union[21] in 2015 (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al., 2017), i.e. 6 352 TWh [22], and constituted the main use of the final energy demand in the continent, followed by the transport sector, whose share has steadily risen from 22% in 1990 to 30% in 2023 (European Commission, 2025h).

Approximately three fifths of the heating and cooling demand takes place in the residential and service sectors, whereas the vast majority[23] of the remaining two fifths is utilised as process heating and cooling in the industry (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al., 2017), as illustrated in Figure 2.3.

In residential buildings and service sector premises, space heating is the predominant use, accounting for 27% of the total final energy demand, followed by hot water, with 4% and space cooling with roughly 1% of the final energy demand. In terms of useful energy demand, the relative weight of space heating and domestic hot water does not differ substantially, but the cooling demand share is higher due to the typically higher efficiency of the space cooling equipment. Concerning the cooling demand, various estimates (Werner, 2016;

[20] As defined by Fleiter et al., the final energy demand is the energy input to the heating unit at the final consumer. This excludes the ambient heat in heat pumps (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Martin et al., 2017). If efficiencies of heating and cooling generation are taken into consideration, the output would be *delivered heat*, whereas the *useful energy demand* would also bear in mind the losses in buildings' distribution system. In the EU-28, delivered heating and cooling in the residential and service sectors amounted to 3 109 TWh (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al., 2017), compared to 3 641 TWh of final energy demand. Albeit delivered energy or useful energy demand provide a more accurate appraisal of the heating and cooling sector, their comparison with the total useful demand entails additional difficulties, i.e. the calculation of the useful energy demand in other sectors, and hence it has been avoided. For further information on the implications of this terminology, the reader is referred to the discussion in Paardekooper (2023, section 2.2.2.).

[21] EU-28

[22] It must be borne in mind that the energy use in the heating and cooling sector is not readily available in Energy Balances, and hence, it must be estimated based on a wide range of statistical sources. A later estimate elaborated by Mandel et al. to the European Commission's tender ENER/C1/2018-494, reached similar values (Mandel et al., 2022), whilst the Hotmaps project delivered a somewhat lower estimate (Pezzutto et al., 2018)

[23] Fleiter et al. estimated that a 5,6% of the total heating and cooling demand, or 354 TWh were used in 2015 for comfort heating and cooling in the industrial sector.

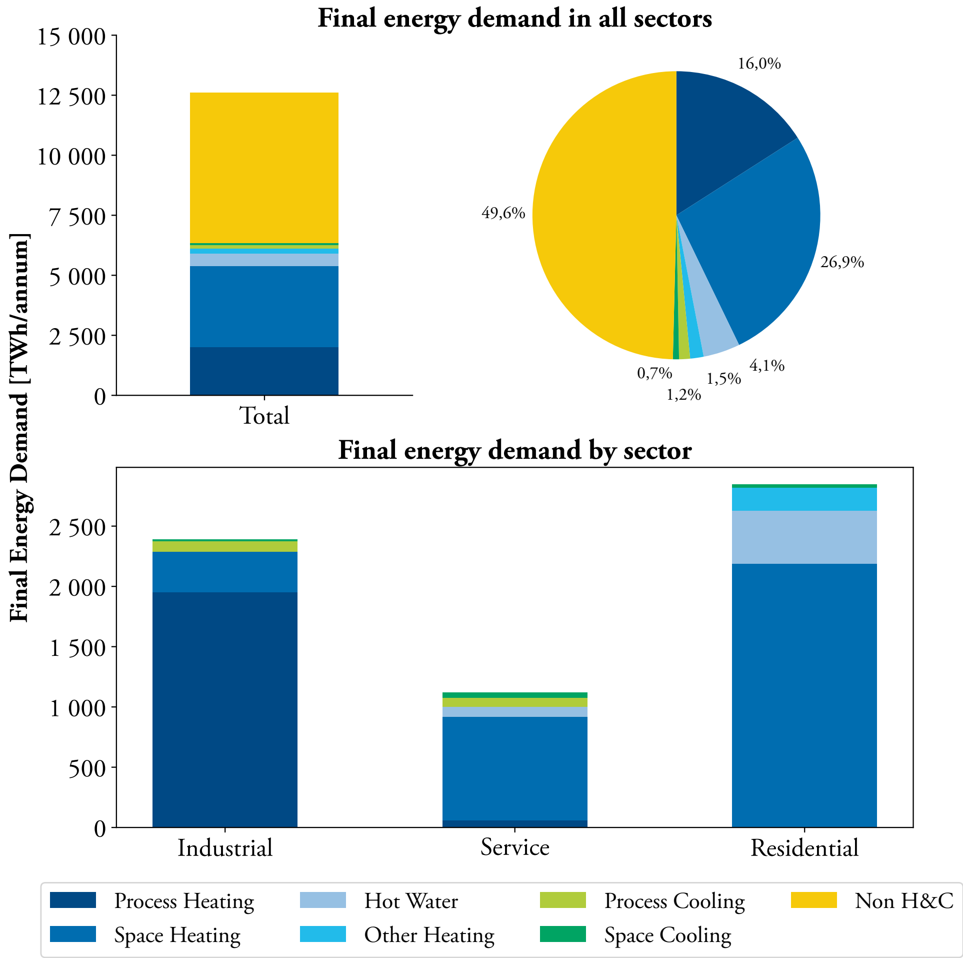

Figure 2.3: Final demand of heating and cooling in the European Union (EU-28) (2015). Sources: (European Commission, 2023b).

Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al., 2017; Pezzutto et al., 2018) provide values of circa 200 TWh, whereas the final energy demand is below 100 TWh.

The previous figures depict the average situation on the continent, and therefore, they hide the existing variation across countries. The differences in climatic, social and building conditions, make the relative importance of the H&C sector vary somewhat, ranging from the lowest in Malta and Luxembourg, with, respectively, 35% and 37% of the total final energy demand [24], and the highest in Latvia, Finland, Romania and Slovakia, with 63%,

[24]The dataset elaborated in the Heat Roadmap Europe project (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Martin et al., 2017) does not provide a national breakdown of H&C shares, so these have been

63%, 64%, and 72%, respectively. The remainder and vast majority of the countries present shares between 40% and 60%. Concerning the distribution among uses, space heating and domestic hot water predominate in all countries, and only in the two insular Mediterranean countries of Malta and Cyprus, space cooling plays a major role. In the other Southern Countries of Spain, Italy and Greece, space cooling is relevant, but the weight in the total heating and cooling demand is small, as can be seen in Figure 2.4. In the rest of the Old Continent, space cooling plays a negligible function, although it has been forecast to rise in the future as the climate continues to warm (Fleiter, Steinbach et al., 2017).

In the residential and service sector, the current heating and cooling demands are the result of a combination of factors, which can be decomposed into two main categories: the total floor area and the specific heat demand per unit of floor area. The former is marked by the evolution of the total population as well as the household sizes and service sector floor areas per person. The latter are shaped by, among others, prevalent climatic conditions, the physical characteristics of the building stock such as envelope insulation or dwelling types, and user behaviour.

Generally, the total population in the European Union has remained rather stable since 1990. Although most countries pertaining to the former Soviet block have undergone population losses, these have been compensated by population growth in the other countries (European Commission, 2025f). This moderate evolution has been nonetheless shadowed by the significant increments in the available floor area per person, which has developed significantly; for instance, it rose by 22% between 1990 and 2020 (Serrano et al., 2017).

Climatic conditions are commonly thought to explain most of the variability in space heating demands across Europe. Nevertheless, colder climates provide higher incentives for more stringent insulation, resulting in specific demands being much more consistent than might have been expected at first (Werner, 2006). According to the Hotmaps project, specific useful heat demands in the residential sector ranged from 30 kWh/m^2 in Malta to 226 kWh/m^2 in Luxembourg [25], whilst, the number of heating degree days [26], varied between 181 in Gibraltar, United Kingdom, to 6 365 in Kiruna, Sweden; i.e. a variation of an order of magnitude higher than the heat demands. Nonetheless, its influence is still significant, and as the climate becomes warmer [27], specific heat demands are likely to fall

calculated based on Eurostat's energy balances (European Commission, 2023b); and concretely, "Final consumption - energy use" for 2015.

[25]Own elaboration based on space heating and domestic hot water useful demands provided by Pezzutto et al. (2018, 2019). Note that the specific figure for a given country may differ somewhat from the values provided by the more recent European Commission's Tender ENER-C1-2018-494 (Mandel et al., 2022)

[26]The degree-day number is a meassure of the coldness of the climate in a given location (Werner, 1984). These figures have been calculated according to Werner (2006), with 40-year weather station data retrieved from NOAA National Centers for Environmental Information - U.S. Department of Commerce (2001).

[27]For instance, in this century Spinoni et al. (2018) foresee a drop in the number of degree days between 4,9 and 8,4 per annum for the entire continent and an increment in the number of cooling degree days ranging

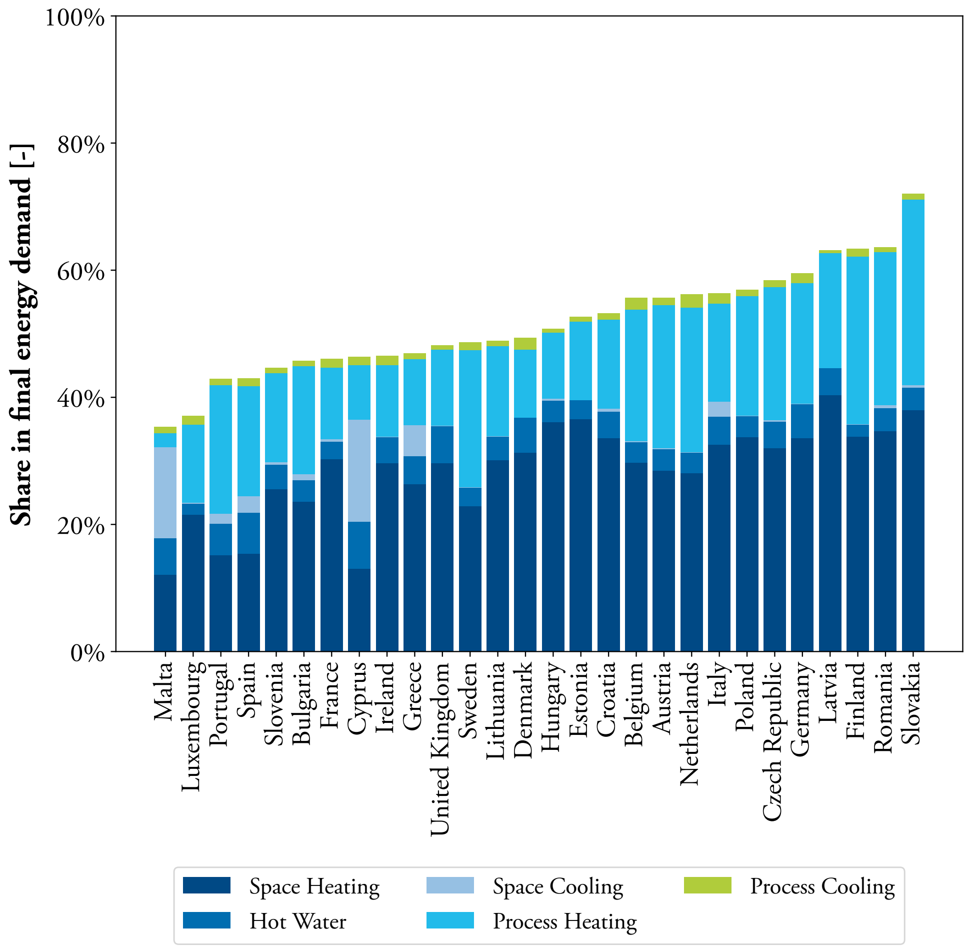

Figure 2.4: Share of heating and cooling in the residential, service and industrial sectors in the final energy demand in Member States of the European Union (2015). Sources: (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Martin et al., 2017; European Commission, 2023b).

and specific cooling demands are bound to increase.

The physical features of the building stock are also significant factors in the specific heating and cooling demands. These characteristics include, on the one hand, building typologies and the composition of the building stock, and, on the other hand, the buildings' thermal characteristics.

from 0,8 to 2,0.

[28]Countries have been sorted after their thermal transmittance values for the decade 1920-1930 as buildings before the pre-war period account for the majority of Europe's building stock (Loga et al., 2015).

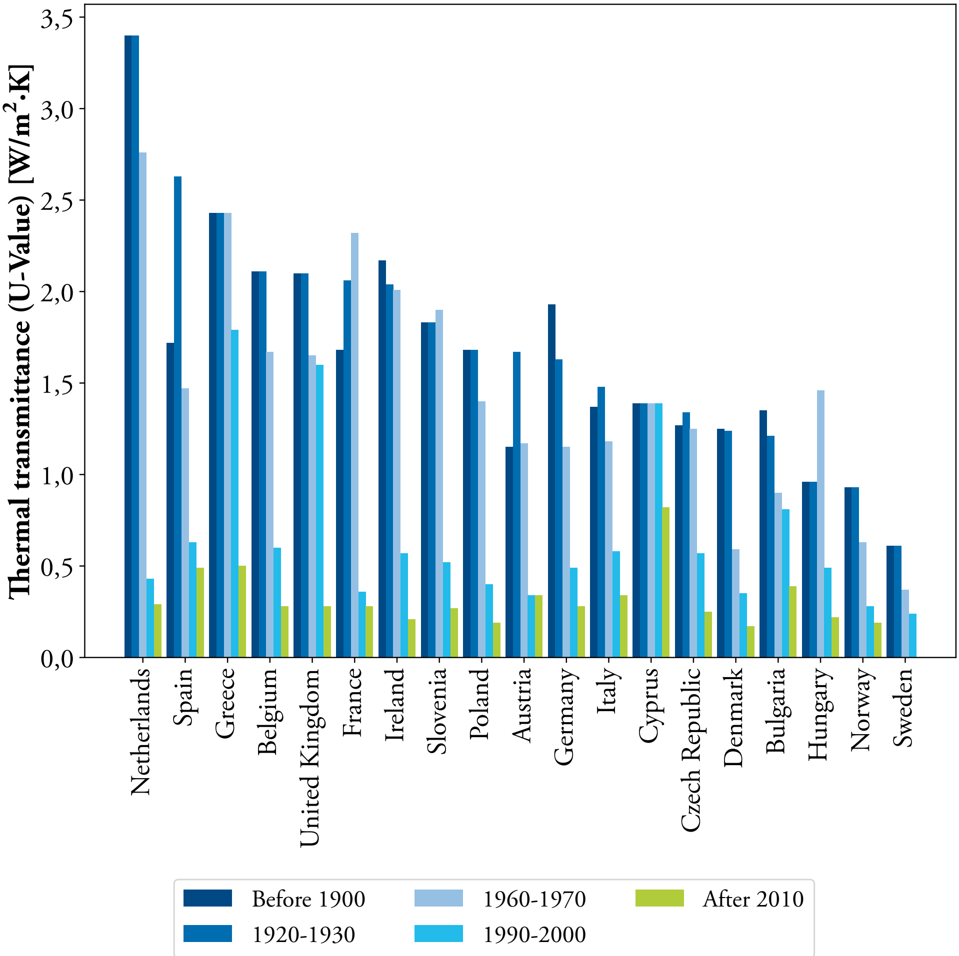

Figure 2.5: Thermal transmittance of exterior walls in 19 European countries over time [28]. Sources: (Loga et al., 2015, Table 7, page 24; Loga et al., 2016).

Concerning the first aspect, single-family homes are likely to present dissimilar values from multi-family buildings, due to the different envelope-area to floor area ratios. For example, in Spain, single family homes present specific heat demands ranging from 40% higher to twice as high [29] as multi-family buildings (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2011); in Denmark, a similar pattern is present although the differences are relatively small (Nielsen & Grundahl, 2016); in Sweden, the opposite occurs

[29]Own elaboration based on reported final energy demand and average floor area per building type and climatic zone.

and multi-family buildings have higher heating demands than single family dwellings [30] [31]. In addition, the share of building typologies varies broadly across Europe, and the share of the population living in multi-family dwellings ranges from a mere 7% in Ireland to 65% in Spain and Latvia (European Commission, 2025a).

Regarding the second issue, the thermal features of the buildings substantially affect the heating and cooling demands of the buildings. These include, among others, the thermal transmittance of the building envelopes, thermal mass, window areas, orientation or architectural design (e.g. roof overhangs). Regarding the first parameter, the thermal transmittance (U-Value), in Europe, building regulations have promoted their reduction, especially after the 1970s Oil Crises, in the pursuit of diminishing the buildings' heat demands as illustrated in Figure 2.5. Concerning the thermal mass, it has a double benefit. On the one hand, it may directly reduce the heating and cooling needs in climates with substantial daily temperature variations, and on the other hand, it may facilitate load shifting (Ingvarson & Werner, 2008; Hedegaard et al., 2019).

User behaviour refers to the different actions taken by the occupant that may affect the heating and cooling demand of a building. These actions include building occupancy, temperature set points, operating hours, window openings, use of appliances and so forth. As an example of the influence of these factors, Andersen et al. reported a one order of magnitude difference [32] between the heat demands of 290 identical row houses (Andersen, 2012). Besides its impact on specific heat demands, consumer behaviour also significantly affects load value and hence, required heating equipment temperatures, which, in turn, may constrain heat production technologies.

Users' patterns are both the result of personal preferences and economic conditions (Delzendeh et al., 2017) such as income and energy price levels. The interplay of the different economic factors leads to lower demand levels than anticipated in poorly insulated buildings and, conversely, higher demands in thermally tight buildings (Gram-Hanssen & Hansen, 2016). In building renovations, this discrepancy between calculated and actual heat demands has been termed *rebound effect* (Galvin, 2014), and may be considered as a corollary of Jevons' paradox (Jevons, 1866, VII Of the Economy of Fuel). The lower specific cost of reaching a given temperature enables the consumer to afford a set-point temperature increment, which, in turn, gives rise to a lower-than-expected heat demand reduction.

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[30] Own calculations based on annual heat demand per building type and total floor areas (Energimyndigheten, 2025a, 2025b). Similar values are provided by Werner (2017a).

[31] This is likely explained by the lack of individual metering in Swedish multi-family buildings (Teli et al., 2021). Additionally, Werner, in personal communication, suggests two other explanations. Firstly, statistics account for final energy rather than delivered or useful energy and detached houses are mainly equipped with heat pumps. Secondly, the living space per capita is higher in single-family houses, so similar personal demands such as domestic hot water lead to lower demands per floor area.

[32] Specific heat demands range from 9,7 kWh/m^2 to 197 kWh/m^2.

2.1.2 Energy sources

Figure 2.6 illustrates the heat sources [33] in European [34] households and service premises according to Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al. (2017) [35]. From this graph, it is clear that the heat provision in Europe is utterly dominated by fossil fuels, with nearly two-thirds of the heat supply, and especially by natural gas, which delivers almost half of the space heating and domestic hot water requirements. District heating, regardless of ultimate energy input, provides circa 12%, similar to biomass and electricity. Concerning this latter one, joule heating predominates with 9% of the delivered heat, whereas heat pumps only reach a mere 3% of the delivered heat.

The foregoing figures only reflect the mean situation across Europe. Nonetheless, there is a noteworthy heterogeneity across Member States. As illustrated at the bottom of Figure 2.6, in 2015 direct use of fossil fuels ranged from a mere 6% in Sweden and 10% in Finland to over 80% in the United Kingdom, Netherlands, Belgium, Ireland and Luxembourg. The most common renewable energy source, biomass, also presents substantial variation, reaching a market share higher than 40% in Croatia and Romania, whereas in two-thirds of the countries it provides less than 20%. Concerning heat pumps, as of 2015, they solely delivered a substantial fraction of the heat demand in Sweden, accounting for 15% of delivered heat. District heating penetration also presents broad variations, with high market shares in Nordic and Baltic countries, moderate shares in Central and Eastern Europe and low penetration in Western and Southern Europe.

The prior figures based on delivered heat distort somewhat the primary energy sources used for heat production, especially in those countries with high use of electricity and district heating. Were primary energy to be employed, as done by Bertelsen and Mathiesen (2020), biomass would have a higher weight, thanks to its ample use in district heating systems and low-efficiency stoves.

Concerning the evolution of heat sources, the last three decades have seen a diminishing role of coal and oil, which has been compensated by a higher share of natural gas (Bertelsen & Mathiesen, 2020). Furthermore, biomass use has steadily risen (Bertelsen & Mathiesen, 2020) and individual heat pumps have experienced a drastic growth, with a tenfold increase between 2004 and 2023 (European Commission, 2024a).

[33] Note that district heating has been depicted as a heat source, disregarding the origin of the heat, even though it is merely a heat vector. This practice resembles the common denomination of electricity as a *source* rather than its primary uses.

[34] EU-28.

[35] Note that the later dataset from the ENER/C1/2018-494 tender indicates rather similar values (Mandel et al., 2022).

[36] The term *source* has been used rather loosely as it refers to actual energy sources such as oil, coal or biomass, but also technologies, such as joule heating and heat pumps and heat carriers such as district heating.

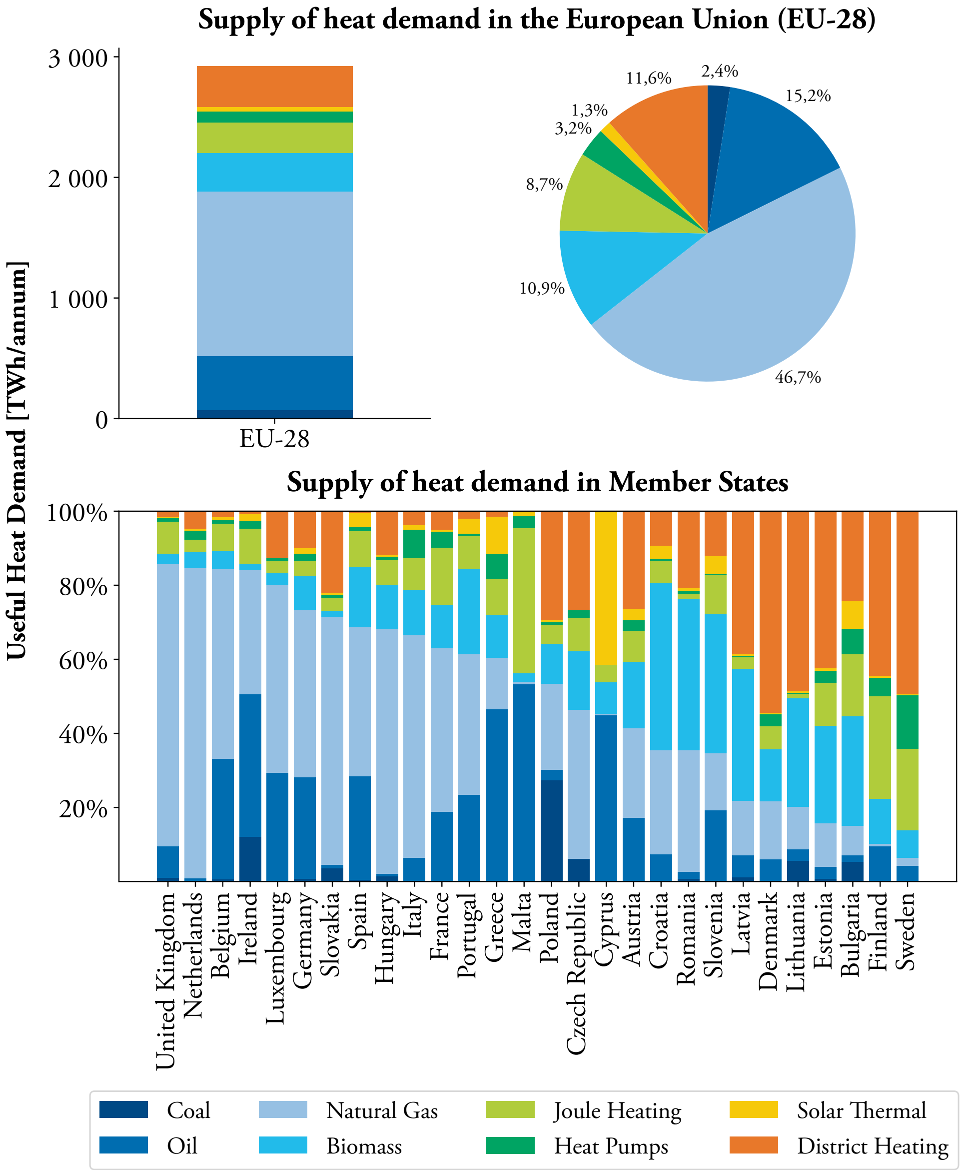

Figure 2.6: Share of useful heat demand in the European Union by *source* [36]in 2015. Sources: Own elaboration based on (Fleiter, Elsland, Rehfeldt, Steinbach, Reiter, Catenazzi, Jakob et al., 2017).

2.2 Alternatives for decarbonisation

The call for decarbonising the European society demands the switch of the heating and cooling sector to no-carbon or low-carbon solutions. This transformation is essential as some other sectors may be harder to decarbonise fully, and the heating and cooling sector may constitute a lower-hanging fruit.

To successfully navigate this endeavour, society has a number of technical solutions at hand. First, the demand for heating and cooling could be reduced through improved thermal performance and the refurbishment of buildings. Second, the current energy carriers could be abandoned, and new, more sustainable alternatives could be embraced.

Most Western European countries have pursued the reduction of thermal demands in buildings since the Oil Crises of the 1970s through tightening building regulations (Papadopoulos, 2016), although some countries such as Germany and Sweden had already taken steps to limit the energy demands of buildings. This strategy has also been encouraged by the European Union through several legislative actions (European Union, 2002, 2012, 2018) and plans (European Commission, 2011a), although clear economic incentives have generally lacked [37]. In Denmark and Sweden the combined effect of economic and regulatory incentives have contributed to a significant reduction in specific heat demands in buildings over the last five decades (Andreasson et al., 2009; Energistyrelsen, 2024a), and Eastern European countries, characterised by a legacy building stock from the communist era with low energy efficiency (Mišík et al., 2024), have also undergone substantial diminutions.

Following these trends, in the aftermath of the oil crisis of 2008 the European Commission proposed in its *Energy Roadmap 2050* strategy a drastic reduction of 72% of specific heat demands [38] in buildings (Connolly et al., 2013). Despite these high ambitions, the overall European progress has been slow during the last 15 years (Odyssee-Mure, 2025) and the renovation rates remain well below target (European Commission, 2020). Furthermore, these high reductions in heat demands typically fail to balance their societal costs with the cost of delivering carbon-free heat and cold.

[37] A clear example of this absence of pricing signals is the typically low taxation of natural gas used for heating across all but four Member States as can be seen in the supplementary material of paper IV. Concerning heating oil, the Weekly Oil Bulletin (European Commission, 2025l) depicts generally higher duties compared to natural gas (The weekly oil bulletin provides taxes as volume-based, which may be converted to energy-based values based on the volumetric net calorific values from Energistyrelsen (2024c) and Eurostat's exchange rates (European Commission, 2025b)). However, the taxation on both fossil fuels is generally lower than on electricity and typically does not internalise all their externalities as shown by Rosenow et al. (2023).

[38] Specific heat demands are not directly provided in the executive summary (European Commission, 2011a) nor in the accompanying impact assessment documents (European Commission, 2011b), but they were derived by the Heat Roadmap Europe team.

Typically, substantial reductions in the space heating demand are feasible with moderate investments, rendering a low marginal cost of heat savings. However, at some point, the cost of saving an additional unit of heat or cold exceeds the marginal cost of supplying carbon-free heat or cold, and seeking further abatements becomes detrimental. This issue has been extensively studied by the Heat Roadmap Europe projects (Connolly et al., 2013, 2016; Paardekooper et al., 2018a) and is developed in depth by Hansen et al. (2016) for four European countries and by Nielsen et al. (2020) for the city of Aalborg in Denmark. Generally, in these projects, it was found that reductions beyond 30-50% of the heat demand were antieconomic and efforts ought to focus on delivering sustainable thermal energy.

Given the limits of heat and cold savings, a transformation of the heat and cold sources becomes necessary. This transition could be based on an array of different sources, each with its own technical and societal advantages and disadvantages. In addition, political views and industrial interests may favour or discard some of them regardless of their benefits for society at large. In the following, a discussion on the various available sources is provided with an emphasis on their pros and cons.

The low-carbon alternatives may be classified in different ways. On the one hand, they may be divided into two broad categories, individual and district-based, depending on the point of production. The former are characterised by the production of heat and cold at the consumer premises. In contrast, a district-based solution is used when at least a fraction is generated centrally and delivered through a thermal grid. On the other hand, they can also be classified into linear heat supply and heat recycling (Gadd et al., 2024). Whereas the former are based on direct use of renewable energy sources, such as geothermal, solar, biomass or electricity, the latter consist of recovering residual heat from another activity.

Individual solutions for heating and cooling generation may, in turn, be based on grids, such as individual heat pumps, Joule heating [39], biogas and hydrogen boilers, or be isolated, such as solid biomass, individual solar thermal installations or a stand-alone photovoltaic installation connected to an electric heating system. The potential and limitations of each of these sources, as well as their technical maturity, are very different.

The proposed categorisation is rather pragmatic, since a mix of energy sources (e.g. biomass), energy carriers (e.g. hydrogen) and technologies (e.g. heat pumps) has been utilised, bearing in mind the particularities of each option.

Biogas or biomethane is an attractive alternative to natural gas, as in principle it would enable a smooth transition from natural gas while reusing most of the existing infrastructure, i.e., the natural gas network and gas boilers. However, the potential of biogas, similarly to other biomass energy sources, is limited compared to the current demands. According to industrial (Alberici et al., 2023) and independent research analyses (Meyer, 2015; Meyer

[39] The term *Joule heating* refers to electric resistive heating.

et al., 2018), biogas production in the European Union could reach approximately 300 - 1 000 TWh per annum [40], compared to a Gross Available Energy supplied by natural gas in 2023 of 3 175 TWh [41]. Furthermore, the biogas scarcity begs the question on whether this energy resource should be dedicated to the production of low-temperature heat in buildings or dedicated to other societal uses, such as the industry or electricity production [42], in which, natural gas may be more difficult to replace.

Solid biomass is a further renewable energy source that could be exploited for the decarbonisation of the heat sector. Furthermore, its use could not only contribute to attaining carbon emission reduction targets but also bring about ancillary benefits such as rural employment (Copus et al., 2006; Lehtonen & Tykkyläinen, 2011; Peters et al., 2015) and wildfire prevention (Marino et al., 2014; Madrigal et al., 2017; Otero & Nielsen, 2017a; Otero & Nielsen, 2017b). However, it presents similar resource limitations to those of biogas. According to the Enspreso assessment carried out by the Joint Research Centre (Ruiz et al., 2019b), all biomass [43] could potentially deliver [44] circa 3 000 TWh (Ruiz et al., 2015, 2019a). Albeit these energy volumes are in the same order of magnitude as the current demands for space heating and hot water, these purposes would compete with other uses beneficial for society, e.g. electricity production, high-temperature process heat, or carbon-based electrofuels such as methanol (Lund et al., 2021). Furthermore, an increment of biomass utilisation could give rise to higher particle and other pollutants emissions if not properly handled (Chafe et al., 2015; Sigsgaard et al., 2015; Heat, 2016; Press-Kristensen, 2022). This increase in air pollution would be likely to occur if biomass were deployed in the residential sector in a decentralised manner since individual boilers lack flue glass cleaning processes that are only cost-effective for large installations.

High-temperature geothermal energy is a *renewable* [45] energy source result of the primordial heat remaining from the formation of the Earth and the decay of radioactive isotopes in Earth's mantle and crust (Gando et al., 2011). Due to its conditions, such as high investment costs and economies of scale, it is only exploited to cater to district heating systems. High-temperature geothermal energy has been extensively utilised in Iceland since the

[40] Note that the industry's estimates are more optimistic.

[41] This limitation in terms of production can also be observed in national potential assessments. For instance, in Spain, the potential annual production was estimated to be circa 20 TWh (Pascual et al., 2011), whereas the Gross Available Energy supplied by natural gas has oscillated around 300 TWh per year during the last decade (European Commission, 2023b). Conversely, in Denmark, biogas has been estimated to be able to provide circa 14 TWh (Energistyrelsen, 2014), which is similar to current demands (European Commission, 2023b). This similarity is explained by, among others, the small role that natural gas plays in the heat supply to buildings (Energistyrelsen, 2024a).

[42] In this case, cogeneration or combined heat and power (CHP) should be prioritised.

[43] All biomass not only includes solid biomass but also biogas.

[44] Medium scenario.

[45] On a human scale, it may be deemed renewable provided that extraction rates are limited. Otherwise, localised depletion could occur.

1930s (Melsted, 2021), and other examples include Munich (Rave, 2023), the Paris basin (Ungemach & Antics, 2006), or Aarhus in Denmark (Jørgensen, 2023).

Solar thermal energy harnesses the sun's radiation to produce heat directly. Solar collectors may be used to produce low-temperature heat up to circa 100°C above ambient temperature (Duffie & Beckman, 2013, page 236), whereas higher temperatures precise some form of concentration. In this latter case, parabolic troughs, Fresnel reflectors or heliostats with a central tower, may be used to reach temperatures up to 1500°C (Zhang et al., 2013), which can be used to generate electricity. Solar thermal energy may be used individually in small installations at each building (Asociación Solar de la Industria Térmica (ASIT), 2020) but also in large plants connected to district heating networks (Heller, 2001; Dalenbäck, 2007; Tian et al., 2019). For space heating and domestic hot water, flat-plate collectors and evacuated tubes are the most common technologies, but concentration technologies have also been utilised (Jensen et al., 2020, 2022). A noteworthy disadvantage of solar thermal energy is the mismatch between heating production and demand, and the competition with other potential sources, which may preclude it from reaching a considerable role in the future (Mathiesen & Hansen, 2017; Hansen & Mathiesen, 2018). Nonetheless, this profile is advantageous for cooling production through absorption chillers (Duffie & Beckman, 2013; Ayou & Coronas-Salcedo, 2020).

Ambient cold arising from bodies of water such as rivers, lakes and the sea is a frequent source for district cooling networks (Looney & Oney, 2007; Calderoni et al., 2019). Sea water has been extensively employed in Swedish district cooling systems such as Gothemburg's (Jangsten, 2020) or Stockholm's (Werner, 2017a). In contrast, other systems such as Paris' (Mairie de Paris & Climespace, 2011) exploited water from the river Seine and Toronto's utilised water from the depths of the lake Ontario (Bélanger, 2005; Robertson & Brannon, 2018). In some cases, such as Paris, the water body is not sufficiently cold during the entire year, so free-cooling is only possible during the winter months, and during the summer months, the river Seine is used as a heat sink for compression heat pumps.

Heat pumps are devices that enable the transfer of heat between different temperature levels. Most often, compression heat pumps employ electricity to power a thermodynamic cycle (Klein & Nellis, 2011), but there also exist other types such as absorption heat pumps, which are thermally driven (Herold et al., 2016).

Individual heat pumps, be they air-source or ground-source (Alberdi-Pagola, 2018) are an energy efficient technology, compared to Joule heating, but they remain more capital intensive compared to the latter (Energistyrelsen & Energinet, 2025). Nonetheless, from an energy systems standpoint, this additional investment may well be compensated by lower investment costs in electricity generation and distribution. Furthermore, ground-source installations may provide the supplementary service of "*free-cooling*" (Alberdi-Pagola et al.,

2016) [46]. According to the Heat Roadmap Europe 4 project, individual heat pumps ought to be the preferred individual alternative (Paardekooper et al., 2018a) due to their efficiency and energy system impacts.

Heat pumps may also be employed for supplying heat and cold to district heating and cooling networks (Frederiksen & Werner, 2013a, section 6.10). They have been employed extensively in Sweden since the 1980s (Persson & Jander, 1986; Averfalk, Ingvarsson et al., 2017; David et al., 2017) and more recently they have gained momentum in the Danish district heating sector (Rasmussen & Alexandersen, 2024). Heat pumps not only enable both the utilization of low-temperature ambient heat such as air, bodies of water, or waste water (Minett, 1994; Bach et al., 2016; Pieper, 2019; Pieper et al., 2019; Persson et al., 2020; Eggimann et al., 2023; Rasmussen, 2024), but also the upgrade of low-temperature heat from a myriad of sources, such as data centres (Romero et al., 2014; Petersen & Hansen, 2018; Oltmanns et al., 2020; Vejrup, 2021), supermarkets (Super Supermarkets, 2019), particle accelerators (Jurns et al., 2014), electricity transformers (Petrović et al., 2022), metro systems (Nicholson et al., 2014; Barla et al., 2019; Lagoeiro et al., 2019), drinking water networks (Hubeck-Graudal et al., 2020), hydrogen production through electrolysis (Dansk Fjernvarme et al., 2021), or low-temperature geothermal energy (Bjelm & Lindeberg, 1995; Mahler, 1995; Leth Hjuler et al., 2015; Aldenius, 2017).

As hinted before, absorption and adsorption heat pumps use heat to either upgrade a low-temperature heat stream to a usable level or produce cooling. In this sense, they are not a heat or cold primary source but rather they use an energy input to deliver another more useful or plentiful, in a similar fashion to compression heat pumps. They have been employed by district heating systems to recover low-temperature heat, e.g. flue gas condensation in an incineration plant (Støchkel et al., 2017) or low-temperature geothermal heat (Elsman, 2009); but also to deliver cooling, either centrally, such as in the district cooling systems of Halmstad, Sweden (Le, 2014) or Helsinki (Wirgentius, 2011) or decentrally at single buildings (Sagebrand et al., 2015).

Hydrogen is an energy carrier, which can be produced from electric renewable energy sources by means of electrolysis (Guðmundsson & Thorsen, 2022). This fuel will likely be essential for the decarbonisation of some sectors such as fertiliser production (International Renewable Energy Agency (IRENA) & Ammonia Energy Association (ENA), 2022; Rouwenhorst, 2022) or iron reduction (Karakaya et al., 2018; Liebreich, 2023) and in combination with other elements in the production of electrofuels (e.g. ammonia or methanol) for shipping and aviation (Mathiesen et al., 2015; Ridjan, 2015; Brynolf et al., 2022). Additionally, European natural gas associations and operators have touted the public and policy-makers at European level (Hydrogen Europe, 2022; Szabo, 2022; Kurmayer, 2023; Vezzoni, 2024) and individual countries such as Germany (Schmude et al., 2024) or

[46] Free-cooling is typically understood as the provision of cooling with the sole provision of energy to circulation pumps.

the United Kingdom (Vezzoni, 2024) to expand the use of hydrogen to all uses currently covered by natural gas, and specially the heating sector. They argue that the exploitation of the existing extensive gas grid and boilers would underpin a seamless transition for the consumer. However, although some researchers support this idea (Nuttall & Bakenne, 2020), most studies, such as Guðmundsson and Thorsen (2023) and Korberg et al. (2023) and systematic reviews (Rosenow, 2022, 2024) highlight that hydrogen should be reserved for hard-to-abate sectors. The utilisation of hydrogen for providing space heating and hot water in buildings would bring about higher costs and require higher amounts of renewable electricity and materials, mostly due to the poor efficiency of hydrogen production.

Residual heat stemming from other activities, chiefly industrial, may also be recycled for the provision of space heating and hot water in buildings. This waste or excess heat [47] can be transported from an industry to a single building, but most often it is integrated into a district heating network. Depending on local availability, various sources such as cement (Borgholm, 1993), steel (Dalkia, 2009; Konovšek et al., 2017) or aluminium (Haraldsson et al., 2019) production, crematoria (Petersen, 2017) or paper mills (Pedersen, 2009) have been exploited. Residual heat from industries currently provides 10% of the heat supplied by Swedish District Heating systems (Statistiska centralbyrån (SCB), 2025) and in Denmark it reaches around 4% (Energistyrelsen, 2024b) of the heat production. Moreover, several European projects such as Heat Roadmap Europe (Persson et al., 2014), sEEnergies (Manz et al., 2021), Hotmaps (Manz et al., 2018; Aydemir et al., 2020), or international studies (Spie Batignolles, 1982; Miró et al., 2015) have identified a significant potential at a European scale, although very unevenly distributed. For instance, Manz et al. (2021) suggested that 72 TWh could be available at 55 °C in the EU-28 even after substantial efficiency improvements within the analysed industries.

Another type of surplus heat is that generated in a thermal power plant through cogeneration or combined heat and power (CHP) (Andrews et al., 2012). This source played a significant part in the development of district heating in Denmark (Johansen, 2022) and was the primary driving force for early district heating adoption in Sweden (Werner, 2017a). In a European context, the existing potential is substantial as Persson (2015b) identified circa 2 200 TWh of waste heat from power plants, albeit only a small fraction thereof would be feasible to utilise due to geographic constraints. Furthermore, the available heat stemming from power plants is bound to decrease as wind and solar power grow in the European electricity mix. Nonetheless, cogeneration heat stemming from biomass (Paardekooper et al., 2018a), hydrogen (González-Salazar et al., 2020) or nuclear plants (Schmidiger, 2013; Leurent, Da Costa, Jasserand et al., 2018; Leurent, Da Costa, Rämä et al., 2018) could still be highly relevant in a decarbonised energy system.

[47] Over the last decade, among researchers and practitioners, there has been a somewhat Byzantine discussion on the proper term for the heat that may not be useful for the industrial process but may be repurposed for heating buildings. In this thesis, any of these terms will be used indistinctively.

Excess cooling may also be utilised to provide cooling in individual buildings or feed a district cooling network. A common example is the simultaneous production of district heating and district cooling with a heat pump, as in the case of the city of Stockholm (Nyström, 1998; Levihn, 2017) and Helsinki (Riipinen & Wirgentius, 2011), but there exist other options such as the cold recovery from a Liquefied Natural Gas terminal located in Barcelona (Revista Técnica de Medio Ambiente (RETEMA), 2024).

This brief examination has shed light on the potential and limitations of the various sources available for decarbonising Europe's heating and cooling supply and it shows that none of the alternatives constitutes a silver bullet; an intelligent combination of sources adapted to local conditions and societal preferences will be necessary. In addition, some sources are only viable when rolled out centrally through district networks, and these systems also enable an intelligent combination of different sources.

Chapter 3

District Heating and Cooling

District heating and cooling is a thermal energy transport infrastructure that connects one or more heat and cold producers with consumers by means of a network of pipes.

The three main components of a district heating system are a heating production plant, a network of pipes that distribute the heat, and various types of heat users, such as residential buildings, or commercial premises.

3.1 Elements

This section deals with the three main parts of a district heating system: production, distribution and connections to heating and cooling users.

3.1.1 Production

Heat and cold supply encompasses all the units that transform various energy streams into heat and/or cold at an adequate temperature to be distributed.

There exists a myriad of heat sources for district heating and cooling, but as previously mentioned they may be broadly classified into two main categories, linear heat supply and heat recycling.

The former category consists of the production of heat (or cold) as the primary activity. Examples of this are heat-only boilers, heat-only geothermal, solar thermal, electric boilers or ambient heat with the aid of heat pumps.

Recycling heat aims to take advantage of heat that "*would otherwise be wasted*" (Frederiksen & Werner, 2013a, page 21). In this case, heat or cold production is an ancillary activity.

Cogeneration, industrial heat recovery, cold recovery from natural gas regasification, waste heat from data centres, or hydrogen and electrofuel productions are examples of heat recycling.

Each source comes with its own potential and limitations as described in detail in the foregoing section, but there is, nonetheless, a common trend towards the future. Whilst in the past, abundant and energy-dense fossil fuels delivered high-temperature heat with non-existent or minor sensitivity to temperature, most of the future heat sources will only provide cost-effective heat at lower temperatures.

These future heat sources, such as solar thermal, heat pumps, waste heat or geothermal energy, present lower investment and operation costs the lower the production temperature is (Averfalk & Werner, 2020; Geyer et al., 2021), thus requiring a transformation of district heating systems.

3.1.2 Transport

A network of pipes distributes the heat from the production plants to all consumers in an analogous way to a potable water network or an electrical grid.

Initially, steam was chosen as the preferred medium in the first district heating systems developed in the late 19th century. Low fuel costs, lower investment needs for substations, and ease of transport paved the way for the preference for steam (Frederiksen & Werner, 2013a; Lund, Werner et al., 2014; Averfalk, Werner et al., 2017).

Nevertheless, high heat losses in the distribution network and low heat production efficiency have relegated steam to a relic of the past. It survives in some systems such as New York's, Paris's, or central Frankfurt, where high demand density has probably contributed to maintaining its cost-effectiveness. In other systems, steam has been replaced by hot water, such as in the cases of Salzburg and Munich in the first decade of the 21st century (Averfalk, Werner et al., 2017) and more recently Copenhagen, which completely phased out steam in 2020 (Hofor, 2021; Goodstein, 2022).

Nowadays, water is the near-universal transport medium, although other media such as carbon dioxide have been proposed (Weber & Favrat, 2010; Henchoz et al., 2012, 2015; Pedersen et al., 2024; Ungar et al., 2024).

Water presents a number of advantages over steam. It leads to higher electrical efficiencies in combined heat and power (CHP) plants, the lower temperatures generate lower heat losses and water also leads to lower pumping costs in the network. For instance, in the late Copenhagen system, the operation and maintenance cost of the steam network used to be 12 times the cost of the water grid (Hansen & Dehbashi, 2012).

Most often, district heating and cooling networks are composed of two pipes, one supply, which leads the hot or cold water to the consumers and a return pipeline, which sends back the cooled down or warmed up water to the production plant (Frederiksen & Werner, 2013a, section 8.10). These media pipes can be within the same insulation, the so-called *twin pipes*, illustrated in Figure 3.1 or each in its own insulation and jacket pipe. Nevertheless, other possible configurations have been employed according to local circumstances, such as in Iceland, Halmstad or the Parisian suburb of Chevilly-Larue.

In Iceland, one pipe solutions have been used with the goal of reducing investment outlays (Frederiksen & Werner, 2013a, section 6.8.5). In this case, the return water is simply disposed of in the wastewater network, leading to a non-negligible waste of energy. A similar approach is unfortunately applied to many steam substations of the Paris system.

Another concept is the three-pipe system proposed by Averfalk and Werner (2018) and Averfalk et al. (2019) and implemented in the new Halmstad neighbourhood of Ranagård (Norrström et al., 2022). The third pipe is used for recirculating the uncooled, by-passed

Figure 3.1: Welding of a twin pipe in Gelsted, Denmark. Source: the author.

water, so it does not mix with the cooled down water. This solution aims to guarantee a low return temperature all year round.

The geothermal-based system operated by SEMHACH in the Ile-de-France cities of Chevilly-Larue, L'Haÿ-les-Roses, and Villejuif operates an average of 3,2 pipes in parallel with the aim of better exploiting the geothermal source (Faessler, 2015, 2016; Faessler & Lachal, 2017; SEMHACH, 2023).

3.1.3 Connections

Substations constitute the interface between the district heating network and the internal heating or cooling systems of consumers. Substations are responsible for preparing domestic hot water and delivering space heating and space cooling, be it to a hydronic or an air handling system.

According to Frederiksen and Werner (2013b), a large number of possible configurations for substations exists, depending on the production of space heating and domestic hot water, the presence of cascading or not, etc. However, for the sake of brevity, this exposition will be limited to the most common types.

Direct and indirect connections

Concerning space heating and cooling, substations may be classified into two main categories depending on the presence of hydraulic separation between the district heating system and the internal space heating and cooling systems. In systems with direct connection, the district heating water circulates through the consumers' internal systems, e.g. radiators or floor heating as illustrated in Figure 3.2 [48]. In contrast, in systems with an indirect connection, district heating water releases its heat to the internal heating systems through a heat exchanger as depicted in Figure 3.4 [49].

In case of an air-based space heating system such as that of the Canadian Drake Landing Solar Community, an indirect connection becomes indispensable (Mesquita et al., 2017).

Substations with direct connections present as a main advantage their simplicity, as they are typically only equipped with a differential pressure controller. On the contrary, substations with indirect connection contain a heat exchanger, a pump, an expansion tank and more complex monitoring equipment.

[48] Note that the substation is only equipped with one heat exchanger for domestic hot water preparation.
[49] Note the two heat exchangers, one for space heating and the other for domestic hot water.

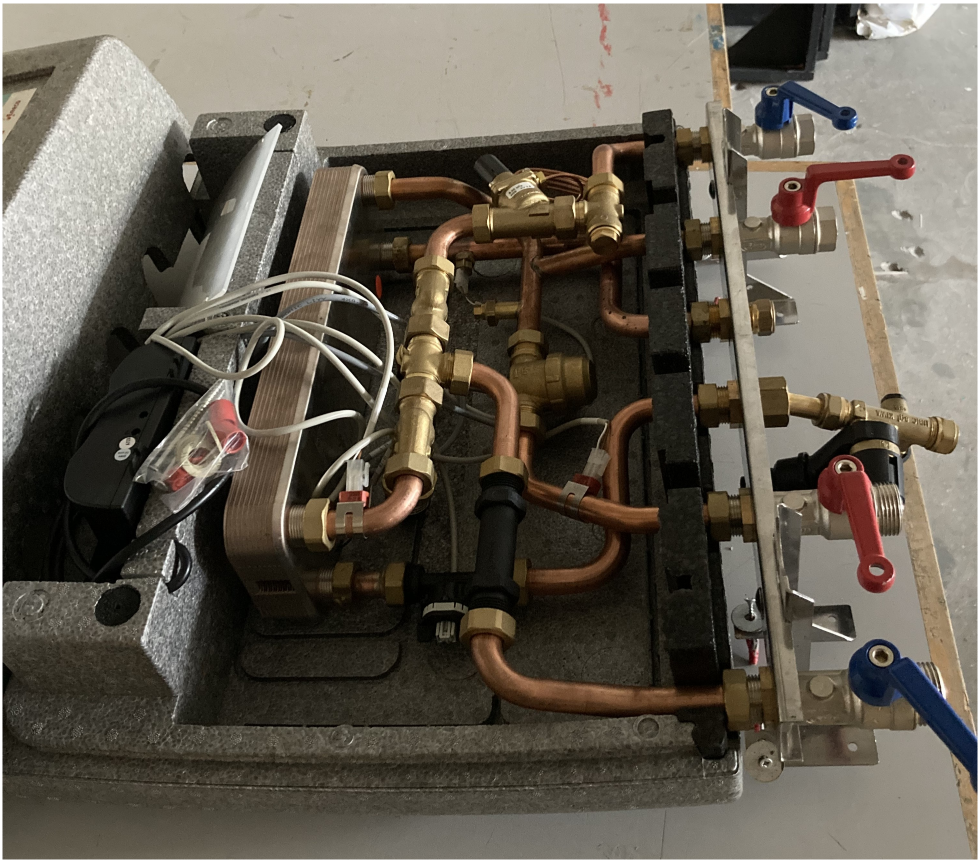

Figure 3.2: Substation with direct connection for space heating and instantaneous preparation of domestic hot water in Rotterdam, the Netherlands. Source: the author.

The simplicity of direct connections translates into lower investment cost, fewer errors (Fogh Hansen, 2013), and lower return temperatures (Andersen, 2024).

However, substations with direct connections demand tighter pressure constraints in the design and operation of the network, and they pose a higher risk of flooding, especially in the (unlikely) event of pressure shock (Frederiksen & Werner, 2013a, page 369).

The cost advantage of direct connections is noteworthy in single-family houses, but it is less significant in large buildings, in which the specific substation cost is lower (Energistyrelsen, 2021). This benefit in detached houses and the delivery of district heating to ample suburban areas [50], have probably contributed to their preference in Denmark, especially on the Jutland

[50] According to Danmarks Statistik (2024) 50% of Danish detached homes and 68% of row houses were supplied by district heating in 2024. In comparison only 17% of Swedish single-family homes were connected to a district heating network in 2014 (Werner, 2017a).

Figure 3.3: Substation with indirect connection for space heating and preparation of domestic hot water with accumulation in Copenhagen, Denmark. Source: the author.

peninsula and the island of Funen (Dyrelund et al., 2010b; Bundegaard Eriksen, 2015). In contrast, in countries such as Sweden, where district heating primarily supplies multi-family and service buildings, indirect connections prevail (Novosel et al., 2022).

Accumulation and instantaneous production

Domestic Hot Water (DHW) may be produced instantaneously, i.e., at the time of use or over more extended periods of time and accumulated for later use.

Preparation with accumulation is typically performed in a water tank containing domestic hot water and equipped with an internal coil, through which district heating water circulates (Frederiksen & Werner, 2013a, section 9.6.3). Nonetheless, other solutions, such as the storage of district heating water (Paulsen et al., 2008), have been proposed or the use of an external heat exchanger.

From a hygienic and comfort perspective, instantaneous preparation presents the advantages that the consumer has access to an endless stock of domestic hot water and the risk of legionella proliferation is minimal (Brand, 2014; Yang, 2016). However, modelling and experimental studies carried out by Winberg (1992) showed that water tanks control was easier to perform and hence, typically led to more stable flow rates and temperatures.

From a district heating standpoint, the presence of the accumulator may enable a reduction in the peak heat power load demanded from the district heating network. For instance, investigations carried out by the Danish Technological Institute in the 1980s showed that water tanks could lead to lower peak loads, especially if a flow limiter was installed (Morgenstern & Lawaetz, 1985). More recently, Thorsen and Kristjansson pointed out that a reduction from 32,2 kW to less than 10 kW was possible for a single-family substation (Thorsen & Kristjansson, 2006).

Notwithstanding the benefit of the reduction in the maximum heat power load, the return temperature and the flow rates are more relevant parameters for the district heating system, since they affect the pipe sizing, heat losses and production efficiency. In principle, the health hazard posed by the growth of the Legionella bacteria in the water magazine obliges to maintain the domestic hot water above 50-60 °C (Brand, 2014; Yang, 2016), which would lead to higher return temperatures, especially when the accumulator is nearly full. This preliminary assessment seems validated by Morgenstern and Lawaetz's experimental investigations (Morgenstern & Lawaetz, 1985). These researchers generally obtained lower return temperature for instantaneous preparation, despite the rather low thermal lengths of the spiral heat exchangers of the time [51]. However, more recent *in situ* measurements in Denmark present mixed results. Whereas measurements carried out in existing dwellings (Vesterby Knudsen & Husballe Munk, 2013) reached similar district heating water cooling for both methods, according to Christiansen (2014), lower return temperatures were provided by instantaneous preparation in the newly-built experimental low-temperature area in Lystrup (Kaarup Olsen et al., 2014). Furthermore, water tanks have been able to deliver relatively low return temperatures provided that the return temperature is either limited (Morgenstern & Lawaetz, 1985) or carefully controlled (Tahiri et al., 2023).

In any case, the effect of domestic hot water preparation in a district heating system is determined by the combination of effects from all consumers. This combination may be taken into account by the simultaneity or coincidence factor (Frederiksen & Werner, 2013a, section 5.6.1). Detailed TRNSYS simulations by Braas elaborated with realistic draw-off profiles show lower coincidence factors for instantaneous preparation compared to preparation with accumulation (Braas et al., 2020). Similarly, actual measurements carried out by Knudsen & Munk in the Danish town of Nykøbing Falster indicated that instantaneous preparation caused lower simultaneity factors and hence, lower flows above

[51]The thermal length or Number of Transfer Units was below 2 for the current flow conditions according to the Danish Standard DS 439. For the sake of comparison, the former Swedish District Heating association substation guidelines recommended a minimum thermal length of 3,2 (Energi Företagen, 2016) and Averfalk and Werner (2017) have encouraged moving towards 6-8.

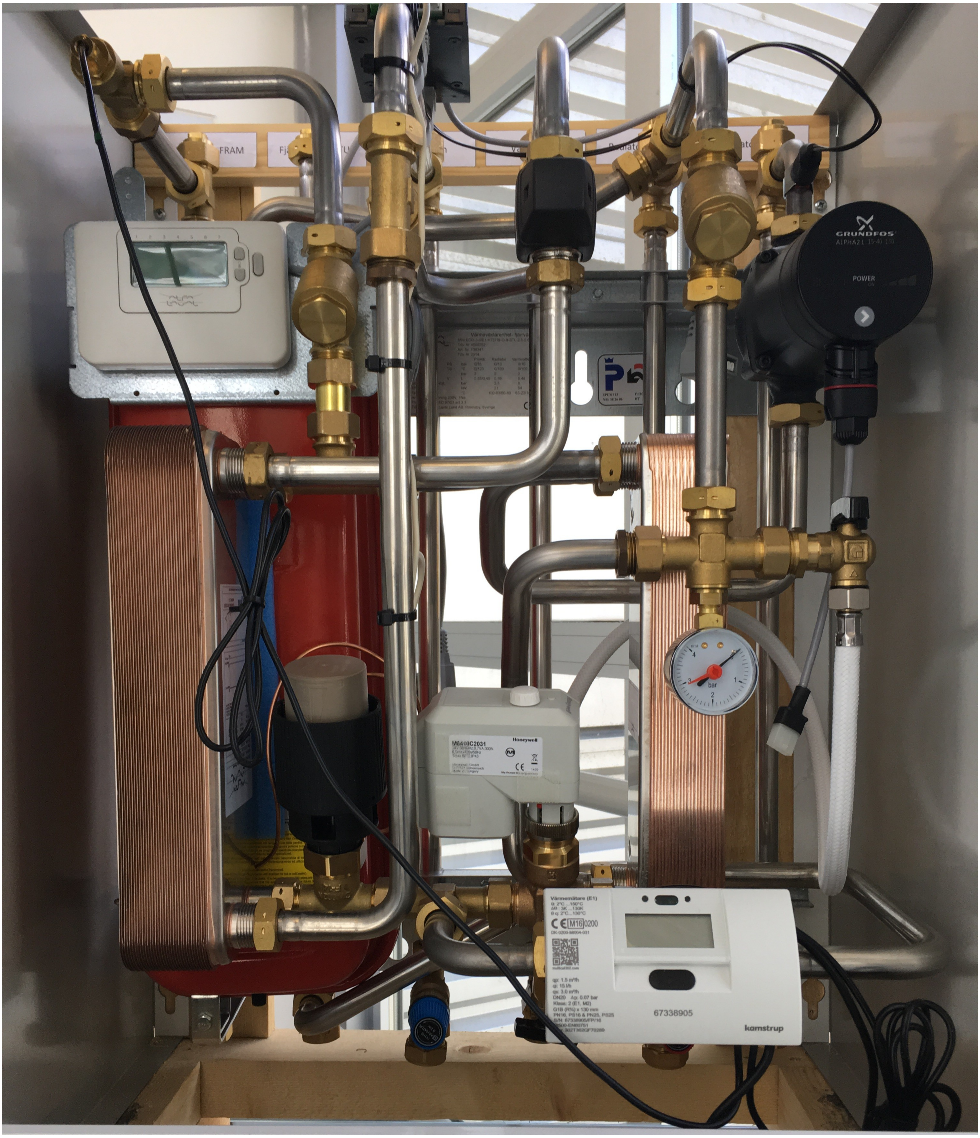

Figure 3.4: Substation with indirect connection for space heating and instantaneous preparation of domestic hot water in Halmstad, Sweden. Source: the author.

five consumers, thanks to the short duration of draw-off events, compared to the longer charging times of water accumulators (Vesterby Knudsen, 2013; Vesterby Knudsen & Husballe Munk, 2013). These results are confirmed by the data presented by Christiansen in the Lystrup experimental area (Christiansen et al., 2012).

The combination of similar or somewhat lower return temperatures and lower simultaneity factors conduct to lower water mass flows in most of the network, as shown by Thorsen and Kristjansson (2006) with an application of simultaneity factors or by Sánchez-García and Møller Andersen (2018) with a detailed dynamic simulation of a small district heating network.

3.2 Historical evolution

This section summarises the historical development of district heating and cooling technology over the last century and a half.

3.2.1 District heating

Aside from historical curiosities such as the district heating system of Chaudes-Aigues in France, which has been delivering heat since the 14^{th} century (Werner, 2013, 2017b), modern district heating was born in 1877, when Birdsill Holly developed a steam network in Lockport, New York ("The Holly System of Steam Heating", 1879).

Steam systems were soon installed in other locations in the United States, and Europe. The system of Manhattan, which has been in operation since 1882 to this date, is a paradigmatic example in the US (New York Steam Corporation, 1932). In Europe, early examples are the system of Frederiksberg in Denmark, commissioned in 1904-1906 (Skov et al., 2007), and the German systems of Hamburg in 1921 or Berlin in 1927, or the city of Paris in 1930 (Werner, 2013).

These early systems constitute the first generation of district heating technology (Lund, Werner et al., 2014), which was also characterised by the use of fossil fuels or waste incineration, sources which were capable of delivering the high temperatures required for steam distribution. Concerning the distribution network, pipes were typically installed in ducts and insulated in-situ (Frederiksen & Werner, 2013a, page 277). Some systems included a return pipe for the condensate, while others dispensed with them.

The high network heat losses of these steam systems, corrosion problems in the condensate return pipes, as well as the significant penalty in electricity generation, pushed engineers to develop a new generation of district heating technology based on superheated water [52].

Similar to first-generation systems, second-generation pipe networks were usually installed in ducts and insulated *in situ* with mineral wool or other materials (Frederiksen & Werner,

[52] The problems of steam and the rationale for using hot water are exemplified in Torroja's discussion of Madrid's University Town district heating, conceived in the 1930s (Torroja, 1943)

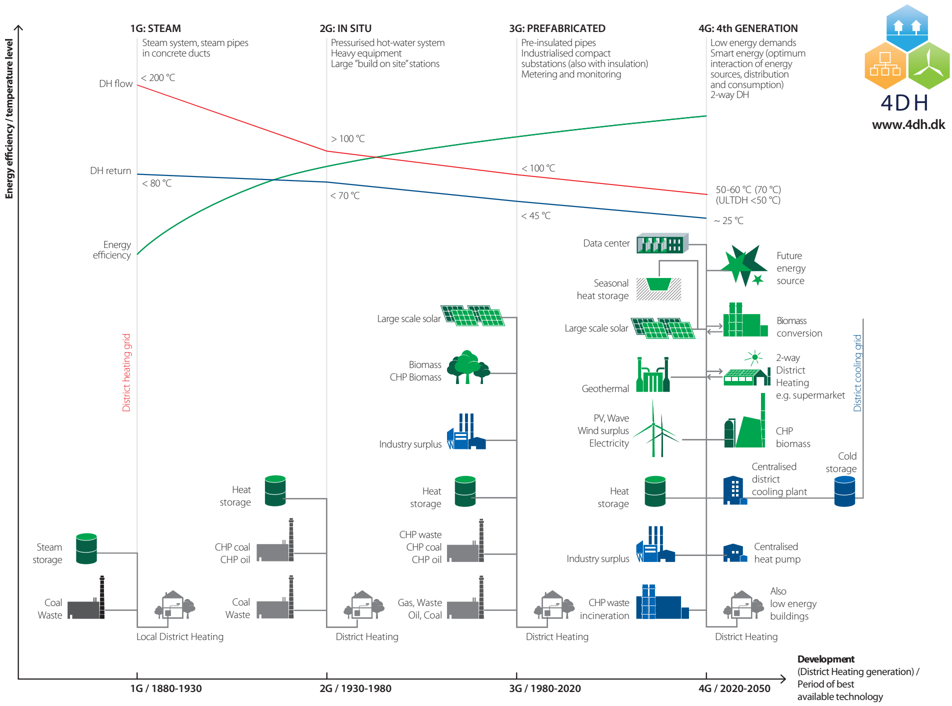

Figure 3.5: Evolution of district heating technology. Source: (Thorsen et al., 2018). Reproduced with permission from the authors.

2013a, page 277). Furthermore, large tube-and-shell heat exchangers and heavy valves were widespread in substations (Lund, Werner et al., 2014).

Early examples of second-generation networks are the system of Reykjavík (Melsted, 2021), which took advantage of the abundant geothermal energy of Iceland, or the numerous systems that were commissioned in Denmark and Sweden in the aftermath of the Second World War [53]. Some remnants of these second-generation systems, such as concrete ducts, can still be found in networks developed in this period [54].

The oil crises of the 1970s ended the unrivalled economic prosperity that Europe experienced since the post-war period, *Les Trente Glorieuses* (Fernández-Villaverde, 2024), and led to a

[53] In Denmark, many cooperative district heating systems were founded in this period and older municipal systems also expanded their coverage (Fjernvarme-Sammenslutningen: Sammenslutningen af fjervarmeværker og -centraler i Danmark, 1970; Skov et al., 2007), resulting on a 14% mean annual heat production growth rate between 1949 and 1969 (Normann et al., 1959; Statistiks Danmark, 2022). In Sweden, the first system was established in Karlstad in 1948 and by 1984, 100 systems had been erected (Werner, 1984).

[54] As an example, Öreundskraft's network in Helsingborg, Sweden, as of 2023 still had a 58,4 km asbestos cement duct (Gurklienė et al., 2023, page 28).

dramatic and nearly unprecedented rise in energy prices (Ritchie et al., 2023). This high cost of energy prompted the district heating sector to evolve towards higher efficiency and lower costs. Cheaper fuels such as coal, or locally-sourced fuels such as biomass and waste, substituted oil and combined heat and power took a more prominent role. Network temperatures were further reduced below 100°C, and preinsulated bonded pipes constituted a major technical innovation (Frederiksen & Werner, 2013a, section 8.1.4.). Furthermore, these pipes commenced to be directly buried in the ground, eliminating the need for ducts and thus enabling a more streamlined roll-out of district heating networks. Other technical developments of this new generation were substations with plate heat exchangers, and in general, more material lean components (Lund, Werner et al., 2014).

In a similar fashion to previous transitions, the diffusion of the new generation was gradual and second-generation systems continued to be built for years to come. For instance, in US military bases in Europe, German-designed systems continued to prefer the use of superheated water, whereas those designed by Danish engineers employed lower temperatures (Zhivov et al., 2006).

As illustrated in Figure 3.5, the general trend in the last century and a half of district heating technology development has been towards lower distribution temperatures, growing diversification in energy sources, and more prefabricated and material lean components. Based on these historical trends and current societal needs of decarbonisation and security of supply, researchers have envisioned the fourth generation of district heating technology (Lund, Werner et al., 2014).

According to Lund et al., fourth-generation district heating should fulfil five different criteria. First, they should have the ability to meet low-temperature space heating and domestic hot water demands. Second, losses in the network should be minimal. Third, they should have the capacity to integrate low-temperature heat and renewable energy sources such as solar or geothermal. Fourth, they should be an integrated part of the entire energy system, including the electricity and gas grids. Fifth, they should be accompanied by an adequate framework to ensure good planning, operation and relations with society at large.

Based on these various criteria, Lund et al. delineate 4th generation district heating as

> *"A coherent technological and institutional concept, which, by means of smart thermal grids, assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. The concept involves the development of an institutional and organisational framework to facilitate suitable cost and motivation structures."*

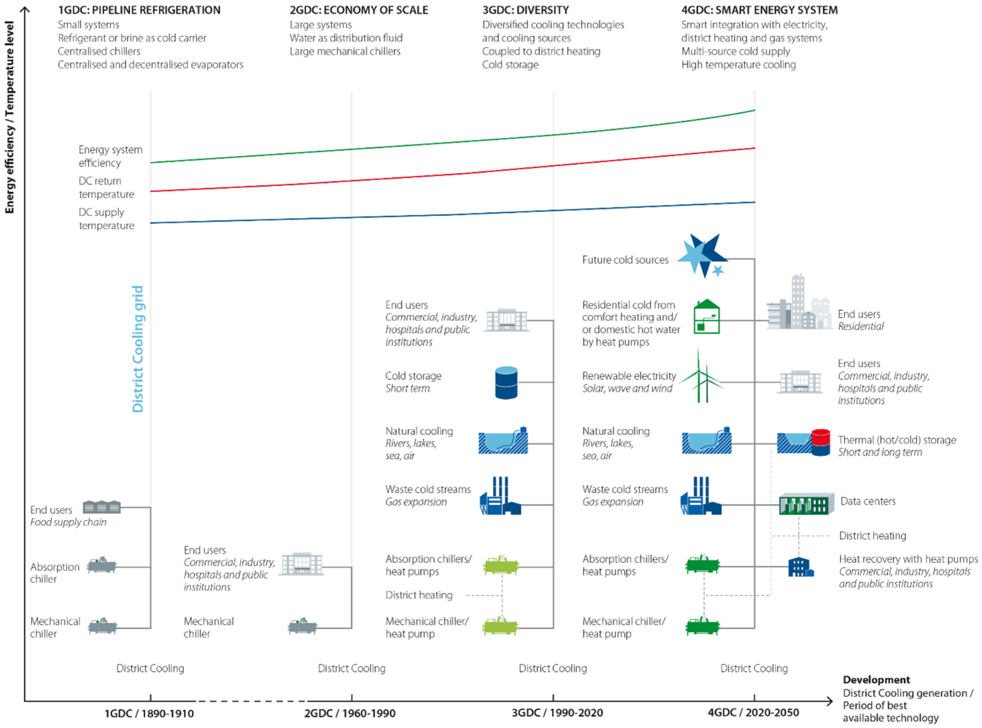

Figure 3.6: Evolution of district cooling technology. Source: (Østergaard et al., 2022). Reproduced with permission from the authors.

3.2.2 District cooling

According to Østergaard et al., district cooling has experienced a technological evolution since the first systems were developed in the late 19th century (Østergaard et al., 2022), following some of the same trends that district heating underwent.

The first generation systems were built in the United States in 1889, Denver (Beach, 1891), and 1890, Saint Louis. These pioneer systems were characterised by the use of a distribution network transporting a refrigerant, e.g. ammonia, from centralised condensers to decentralised evaporators, or brine. To a certain extent and at a different scale, the former resembled current Variable Flow Refrigeration systems (Goetzler, 2007; Aynur, 2010). Furthermore, these early schemes mainly addressed the need for refrigeration rather than comfort space cooling (Østergaard et al., 2022).

In second-generation systems, conceived in the 1960s and 1970s, refrigerants were substituted by chilled water. Another defining feature was the exploitation of economies of scale by producing cold in large compression chillers. In addition, comfort space cooling became the prime demand served. Early examples of this novel technology were the system of Hartford, United States, in 1962 (Jebb, 1961; Mirabella, 1986; TEN Companies Inc, 2003), La Défense area in Paris (Woods, 2023, section 1.4.1.), and the Shinjuku district in Tokyo (Low Carbon Design & Research Institute (LCDRI) & Pan China Construction Group, 2015). More recent projects include the large district cooling networks erected in the Middle East (Østergaard et al., 2022).

The next big leap in district cooling evolution took place in the 1990s after chlorofluorocarbon refrigerants were phased out in the wake of the Montreal protocol (Østergaard et al., 2022). Compared to prior iterations, third generation systems began to utilise of a broader array of cold sources such as absorption chillers, combined heating and cooling production with compression chillers, natural cooling from water bodies or excess cold streams (Østergaard et al., 2022). Last but not least, they incorporated cold storage.

Despite their warm climate, third-generation systems soon took off in the Nordic countries, probably thanks to their long experience with district heating. The district cooling systems of Stockholm (Fermbäck, 1995) and Gothenburg took their first steps in 1995, and were followed by Helsinki in 1998 (Wirgentius, 2011) and Copenhagen in 2010 (Willum, 2017).

According to researchers (Østergaard et al., 2022) and practitioners (Dyrelund & Bigum, 2020), the future of district cooling will be driven by the cross-sectoral integration into a *"smart energy system"* [55], exploitation of the synergies in the simultaneous production of heating and cooling, and a more extensive use of long-term thermal storage. Furthermore, cooling may be produced centrally, as in prior generations or decentrally.

A prime example of 4th generation district (heating) and cooling is the system of Stanford University in the United States, which is able to cover 75% of the heating and cooling demand in joint generation thanks to the thermal overlap (Stagner, 2016). This system also presents another defining feature, ample thermal storage, consisting of two tanks of 36 000 m^3 and 8 700 m^3 for heat and cold, respectively.

Concerning another noteworthy innovation of fourth-generation district cooling, decentralised production, several systems have been erected in Europe. The Minjwater scheme was commissioned in Heerleen, the Netherlands, in 2009 (Verhoeven et al., 2014; Mijnwater BV, 2019) and progressively expanded to deliver 11 GWh of heating and cooling in 2019 (Mijnwater BV, 2019). This system extracts water from an abandoned colliery and transports it through a network of uninsulated pipes to decentralised heat pumps and chillers. Furthermore, the mine is also used as seasonal storage in order to balance the seasonal variations in heating and cooling loads. In Switzerland, the *Eidgenössische Technische Hochschule Zürich*, the Federal Institute of Technology Zurich, has also developed a low-temperature grid with decentralised heating and cooling production for the different buildings in its campus (Gabrielli et al., 2020).

[55] The reader is referred to section 3.4.3 for a definition of *"smart energy system"*.

3.3 European context

Currently in the European Union, district heating has been estimated to cover 8-13% of the heat demand in the residential and service sectors (Connolly et al., 2014; Paardekooper et al., 2018a, page 31; Bacquet et al., 2022). Nonetheless, the penetration of these systems varies widely across countries as illustrated in Figure 3.7. Whereas district heating plays a pivotal role in the Nordic countries and the former Eastern Bloc, its weight in Western and Southern Europe is much lower.

The Heat Roadmap Europe projects have shown that countries with low penetration of district heating have high potential for this technology (Paardekooper et al., 2022). Therefore, the ample differences in penetration rates are not likely the result of dissimilar technical suitability across countries, but rather the consequence of policies and market conditions. For instance, Bertelsen et al. (2021) show how the United Kingdom and the Netherlands pursued the gasification of the heat supply on a large scale, whereas Denmark promoted the growth of district heating after the Oil Crisis as a means of reducing the country's energy dependence. In Denmark, other factors such as the long-rooted "*andelsbevægelse*", the cooperative movement, and the existence of large power plants near main urban centres (Skov et al., 2007), probably also paved the way for early development. In Sweden, the desire of municipal utility companies to achieve certain independence with respect to the large national electricity suppliers (Werner, 2017a) has been proposed as one of the main drivers. Furthermore, in both countries, high levels of trust (Directorate-General for Communication (European Commission) & TNS Opinion & Social, 2018), inclusive institutions (Acemoglu & Robinson, 2012), and the distinctive features of local government [56] (Lidström, 2015), have probably also contributed to the high levels of penetration that district heating enjoys in these countries. On the contrary, the crucial role of the State in the planned economies of Eastern Europe and the extensive urban reconstruction that took place in the aftermath of the Second World War (Woods & Overgaard, 2015), are probably the dominant constituents for district heating widespread adoption in that region.

Regarding the heat sources for district heating, the latest Euroheat & Power's Market Outlook (Piel et al., 2025) points out that the energy transition is well in motion and shares

[56] One of this noteworthy characteristics is that the decision-making process takes place in councils and committees rather than being the sole purview of a single mayor or councillor (Acemoglu & Robinson, 2012), which may favour consensus building as illustrated by Summerton (1992) for the development of district heating in the Swedish town of Mjölby.

[57] The category *CHP* refers to Combined Heat and Power. Concerning the sources for these plants, in the case of renewables the main primary energy source is biomass, except for the case of Iceland, where geothermal energy predominates, and the *other* category generally lacked any further break down, except for Czechia, Hungary and Switzerland, which also use residual heat from nuclear power plants. Heat only refers to production units, which solely deliver heat, typically boilers, but also heat pumps and direct industrial heat recovery. Regarding the sources, *electric* refers to both heat pumps and electric boilers, and *Excess* includes residual heat from industry and the tertiary sector.

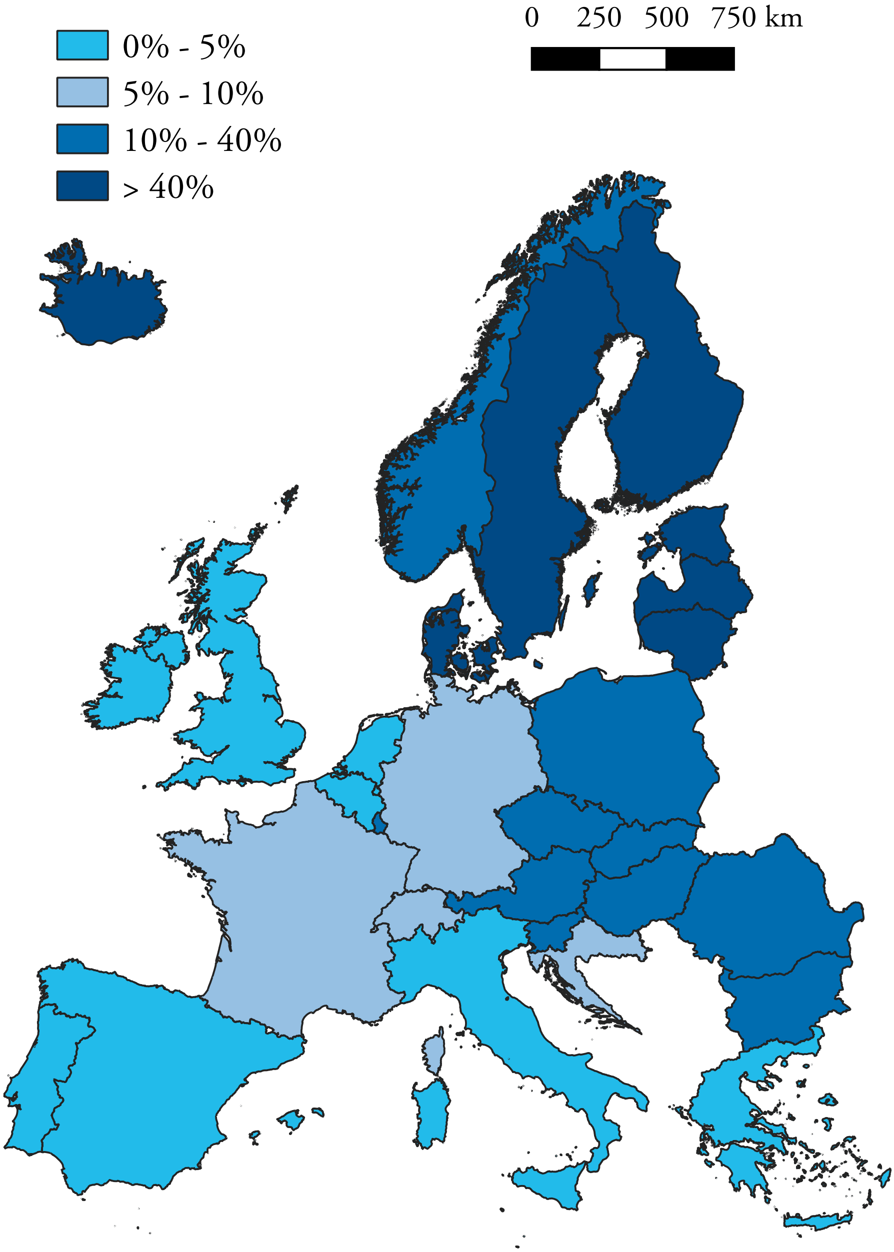

Figure 3.7: Share of district heating in the residential and service sectors. Sources: Own elaboration based on Bacquet et al. (2022, page 30) and Mandel et al. (2022).

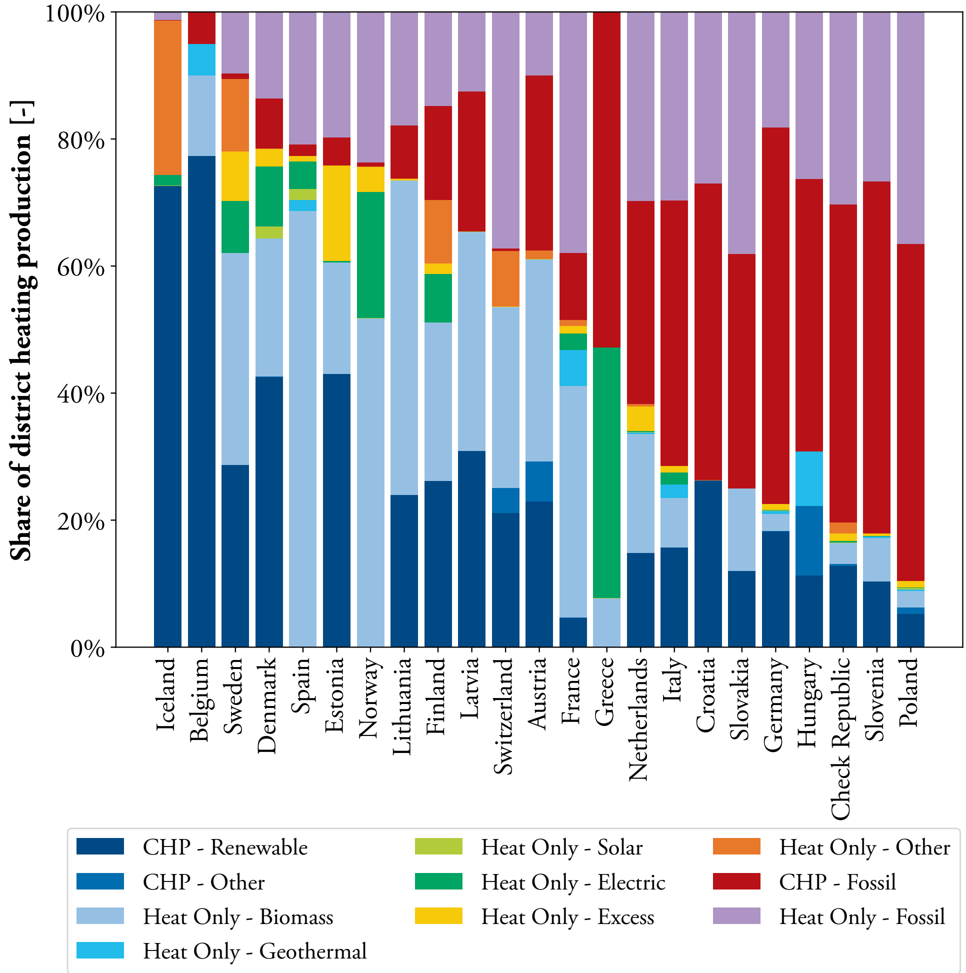

Figure 3.8: Share of production by heat source and technology in selected European countries in 2023 [57]. Source: (Euroheat & Power, 2025).

of renewable energy are increasing across the continent's district heating systems, probably propelled by the tailwinds of high energy and carbon prices (International Carbon Action Partnership (ICAP), 2025).

On the bright side, as illustrated in Figure 3.8, renewable energy sources account for the majority of the heat produced in a good deal of countries. Furthermore, most of the countries have implemented the fundamental idea of district heating, i.e. heat recycling (Frederiksen & Werner, 2013a, page 21), since cogeneration accounts for significant fractions of the produced heat, even if the primary source is not renewable. Nevertheless, in many Eastern European countries, Germany and Italy, fossil fuels remain as the prevailing heat sources, and throughout most countries, direct combustion of fossil fuels still covers a substantial fraction of the demand, neglecting the benefits of cogeneration. Moreover, biomass is the most common renewable energy source, and whereas some countries have taken advantage of their indigenous resources (e.g. Sweden, the Baltic States, Austria or Spain), in others this biomass dependence has led to import dependency (e.g. Denmark (Energistyrelsen, 2024a, page 7)). Finally, some of the most promising future sources, such as geothermal, electric, solar and residual heat, still generally do not contribute substantially to the district heating production mix.

The explanation for the low penetration of these latter potentially more environmentally-friendly sources is probably multifactorial. Nonetheless, a common feature is their higher capital costs compared to most fuel-based sources, which may deter their adoption in many commercially oriented enterprises. In addition, operators, regulators and policy makers may lack experience in these sources or be too cautious in the exploration and adoption of new technologies [58]. Moreover, particularities of each technology and their interaction with the policy framework also contribute to their low adoption. Geothermal exploration entails a high risk, which many single district heating companies may not be able to bear [59], and insurance schemes have only been implemented in a few countries (Fraser et al., 2013; Boissavy & Schmidlé-Bloch, 2014). Heat pumps and electric boilers face taxation levels [60], grid fees design [61] and electricity spot prices [62] that may render them uncompetitive. Residual heat presents unique challenges as, beyond the technical obstacles, it involves not only a district heating operator but an industrial enterprise, for which the sale of heat does not belong to its core business (Päivärinne et al., 2015; Schmidt et al., 2020; Fritz et al., 2022;

[58] As an example, the Spanish 2020 comprehensive assessment on efficient heating and cooling neglected the use of large heat pumps other than ground-source for district heating systems (Ministerio para la Transición Ecológica y el Reto Demográfico & Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2023, section 5.2).

[59] This risk problem is exemplified by the district heating company of Viborg, Denmark, which attempted to harness geothermal heat between 2009-2012 (Rasmussen & Voldgaard, 2012), before the project was cancelled and the company's director fired (Skov, 2012), amid ballooning costs, which were ultimately defrayed by the consumers (Larsen, 2014).

[60] For instance, high electricity taxes held back heat pump installation in Denmark until they were slashed in the period 2018-2020 (Tang, 2021; Skatteministeriet, 2018, Article 1.1), from 400 kr/MWh to 253 kr/MWh (approximately 54 to 34 €/MWh). This reduction triggered a heat pump rush, with the installed capacity increasing from 158 MW to 454 MW in 2020.

[61] For example, Spanish fees and charges lay a substantial weight on contracted capacity. In these conditions an electric boiler would be charged 13 036 €/MW·annum regardless of electricity demand and provided that no electricity is used during peak hours as indicated in the supplementary material of paper IV. In this context, low utilisation values, as expected from an electric boiler, would render very high levelised cost of heat and make electric boilers virtually impossible to deploy.

[62] In the European electricity markets, natural-gas-driven power plants typically represent the marginal producer and thus set the spot price even if their contribution to the electricity mix is minimal (Fabra, 2023). This market design increases electricity prices and therefore disincentivise the electrification of district heating.

Lygnerud et al., 2022).

3.4 Benefits

District Heating and Cooling presents a series of advantages over individual production, which are explored in this chapter.

3.4.1 Economies of scale and economies of scope

In the dawn of district heating systems, economies of scale were vital in the development of these systems (Frederiksen & Werner, 2013a, page 24 & section 11.8). Large boilers had significantly higher efficiencies and lower unit costs than small boilers, which could justify the expense of a piping distribution system.

These economies of scale have nearly vanished for many production units such as boilers or heat pumps, but still remain in others such as solar thermal (Dyrelund et al., 2010a; Energistyrelsen, 2025a), deep geothermal [63], thermal storage (Lund et al., 2016) or heat distribution (Reidhav & Werner, 2008; Frederiksen & Werner, 2013a). With these sources, economies of size may still be strong enough to provide a cost advantage for the satisfaction of heat and cold demands in relation to individual production.

Nonetheless, according to Frederiksen and Werner (2013c), district heating and cooling's main advantage nowadays lies in its capacity to use heat that otherwise would be wasted, exploit renewable energy sources difficult to handle in an individual manner, and couple with the electricity sector to attain a more integrated and cost-effective energy system. These benefits of district heating and cooling have been identified by Frederiksen & Werner as economies-of-scope.

3.4.2 Structural energy efficiency

The ability of district heating and cooling to recycle heat that would otherwise be wasted translates into an increased efficiency of the entire energy system, as less primary energy is required for fulfilling the same energy services (Persson, 2011, 2015a). For instance, the recovery of residual heat at 30°C from a data centre will reduce the demand for electricity, since the heat pump will operate at a higher efficiency compared to an air-source individual

[63] According to Molar-Cruz et al. capital and operation expenditures depend mainly on depth and to a certain extent on flow (Molar-Cruz et al., 2022), so the Levelised Cost of Heat (Aldersey-Williams & Rubert, 2019) would be prohibitively expensive for a small, single building size, installation.

heat pump. Similarly, the retrieval of waste heat from an industrial plant will prevent the use of additional energy to cover space heating and domestic hot water demand.

In an energy system purely based on renewable energy sources, this structural higher energy efficiency will put less strain on biomass resources and will necessitate less wind and solar capacity. Not only will lower installed capacities cause the extraction of fewer mineral resources, but they will also occupy less agricultural or wild land.

According to various studies carried out by the International Energy Agency or the Energy Information Administration of the U.S. Government, renewable energy technologies such as solar photovoltaics, concentrated solar power (CSP) or wind power have substantially higher metal requisites than fossil-based generation (International Energy Agency (IEA), 2021; United States Department of Energy, 2015, Page 290). Therefore, a complete transformation of the world's energy system will require a substantial increase in the extraction of various metals such as copper, iron or nickel. In fact, different research has pointed out that this transformation's metal requirements are in the same order of magnitude as estimated resources (Månberger & Stenqvist, 2018; Tokimatsu et al., 2018; Capellán-Pérez et al., 2019; Giurco et al., 2019; Michaux, 2024), and consequently the risk of depletion is not negligible.

Similarly, renewable energy sources also tend to occupy more land than fossil-based energies [64] and especially than nuclear energy (Smil, 2015; Fritsche et al., 2017; Ritchie, 2022). Thus, the growth of renewable energy sources will require a significantly larger land footprint than the current energy system. This increment in energy plants throughout the countryside has faced strong opposition at times as documented by researchers (Zografos & Martinez-Alier, 2009; Arifi & Winkel, 2020; Temper et al., 2020; Silva & Sareen, 2021; Dechézelles & Scotti, 2022; Susskind et al., 2022) and the press (Christofaro, 2019; Nissen, 2022; Fariza & Planelles, 2023; Plumer & Popovich, 2024; Medina, 2025).

In light of these constraints, there is a strong motivation for aiming for an energy system as efficient as possible, a goal which district heating and cooling can contribute to attaining.

3.4.3 Short term flexibility

District heating and cooling systems are frequently equipped with Thermal Energy Storage (TES) (Gadd & Werner, 2021), which usually takes the form of large water tanks as shown in Figure 3.9, but can also adopt other typologies such as pit storage (Sveinbjörnsson et al., 2019, 2020), depicted in Figure 3.10, aquifer storage (Djebbar et al., 2020), borehole storage (Schmidt & Miedaner, 2012) or cavern storage (Sagebrand et al., 2024). Furthermore,

[64] Note that Ritchie and Smil's values may differ substantially and Ritchie's estimates seem optimistic for some renewable energy sources such as solar in comparison with specific analyses focused on this technology (De Castro-Carranza et al., 2013).

Figure 3.9: Water tanks in Avedørværket, Denmark, each holding a volume of 24 000 m^3 (Andrews et al., 2012, page 71). Source: The author.

although sensible storage is the most common, some installations, especially for district cooling, can also take advantage of the latent heat of fusion (Frederiksen & Werner, 2013a, section 6.15.3; COFELY (GDF SUEZ), 2012). Concerning the time scale, most TES are designed for the short term (Gadd & Werner, 2021), but some systems have also incorporated weekly (Sifnaios & Jensen, 2024) or seasonal storages (Kallesøe et al., 2019; Xiang et al., 2022), sometimes connected to solar thermal installations (PlanEnergi et al., 2005; Marstal Fjernvarme et al., 2013; PlanEnergi et al., 2015; PlanEnergi, 2017).

[65] Notice that the upper lid follows the new design developed by Aalborg CSP (Bobach, 2020; Tange, 2021). In the image it is possible to appreciate the modular design, the gravel ballast cover, as well as the air vents, located between the quadrangular sections.

[66] This graph was inspired by Figure 3 of Grohnheit and Sneum (2023).

[67] During the last five years, spot prices have experienced dramatic changes, mainly driven by natural gas prices. In order to compare weeks with very different absolute price values, a relative price has been calculated for each hour based on the weekly mean price. The underlying assumption is that power-to-heat production will be moved within short time scales to the hours of relative lowest prices, regardless of the absolute level. Note that the absolute levels may play a significant role in those systems equipped with Combined Heat and Power plants, and hence, this approach is a mere approximation.

[68] The weekly number of heating degree days was limited to the range from 100 to 125 in order to represent similar climatic conditions.

[69] Spot prices and and power-to-heat production have been retrieved from Energinet (2025a) and (Energinet, 2025b), respectively. Additionally, a time series of average degree days for the price zone DK1 has been built based on municipality-based daily degree days, weighted by district heating demand. Concerning degree day, daily values have been downloaded from *Danmarks Meteorologiske Institut*, the Danish Meteorological

Figure 3.10: Pit Storage [65] in Høje Taastrup, Denmark with a volume of 70 000 m^3 (Energistyrelsen, 2025a). Source: The author.

Thermal Energy Storage provides several advantages to district heating and cooling systems. A primary benefit is that they enable the decoupling between production and demand, an avail that translates into two similar but conceptually different advantages, peak shaving and load shifting. A secondary benefit is that thermal energy storage provides temporary back-up in case of heat production failure.

Firstly, peak shaving paves the way for the reduction of installed capacities and the constant operation of production units. This advantage may be specially relevant in Central and Southern European systems, which unlike their Scandinavian counterparts, are characterised by very variable profiles primarily due to night set-backs of space heating systems [70].

Institute, through its API (Danmarks Meteorologiske Institut (DMI), 2025). Regarding district heating demand at a municipality level, it has been estimated based on a heat atlas, similar to Aalborg University's *Varmeatlas* (Möller, 2008; Möller & Nielsen, 2014), elaborated on building data retrieved from *Bygnings- og Boligregistret (BBR)*, the Danish Building Registry through *Datafordeler*'s API (Klimadatastyrelsen, 2025), and average heat demands (Nielsen & Grundahl, 2016).

[70] As an example, the reader may compare the district heating load patterns in Italian (Guelpa et al., 2017; Manente et al., 2019) and Spanish networks (Gavaldà-Torrellas et al., 2015; Rey-Hernández et al., 2023) or natural gas in Belgian households (Jebamalai et al., 2020), which show substantial demand increases during the mornings and a drastic drops during the night, with district heating profiles in Danish (Pálsson et al., 1999; Marguerite et al., 2018) or Swedish systems (Gadd & Werner, 2013; Holmér et al., 2020), in which it can be appreciated that heating demand is more evenly distributed throughout the day.

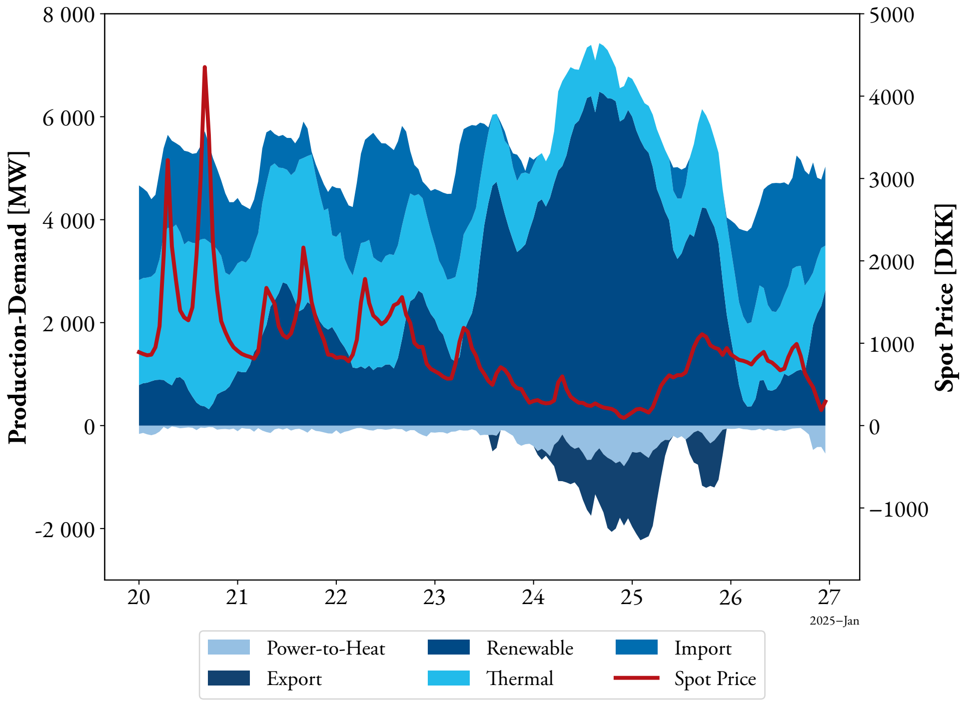

Figure 3.11: Electricity production and demand during a week in Denmark [66]. Sources: (Energinet, 2025a, 2025b).

Secondly, load-shifting, i.e. the production of heat and cold in advance in moments of lower costs or limitations. District heating, in connection with power-to-heat technologies and cogeneration, may facilitate a cost-effective integration of non-dispatchable electricity energy sources. In times of low production of wind and solar power, combined heat and power plants may cover the production gap, while in periods of excess intermittent renewable energy production, heat pumps and electric boilers convert electricity into heat, which is stored for later use.

This load-shifting of heat production in district heating is illustrated in Figure 3.11, which shows the different types of electricity production and demand in Denmark. As appears from the image, periods of high renewable production lead to a drop in market prices, which trigger an increase in the use of heat pumps and electric boilers in district heating systems and exports to nearby countries. This behaviour can also be observed in 3.12, which shows the relation between electricity prices and use of power-to-heat technologies in a more systematic manner. As depicted in the chart, most electricity use takes place in those hours with prices below the average.

This sector coupling and flexible district heating production are some of the backbones of

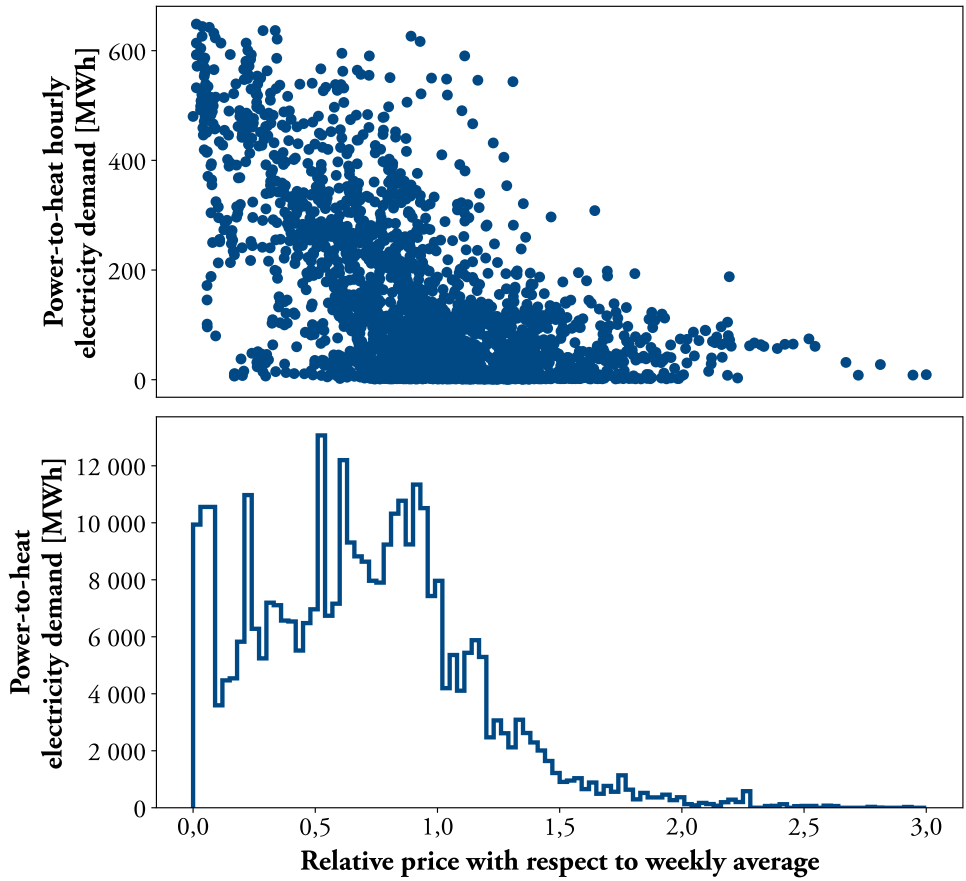

Figure 3.12: Power-to-heat electricity use as function of the spot prices in price area DK1 [67] during mild winter weeks [68] in the period 2022-20. Various sources [69]

the Smart Energy Systems concept, devised by Lund:

> *Smart energy systems* are defined as an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system (Lund, Hvelplund et al., 2014).

[71]The cost of a Tesla Power Wall corresponds to the total installation cost as published by a Spanish newspaper (Escribano, 2023). Similar values for behind-the-meter small residential installations can be found in other European countries (International Renewable Energy Agency (IRENA), 2024, page 150). The investment cost on a utility-scale sodium–sulphur (NaS) battery was retrieved from the Danish Technology Catalogue (Energistyrelsen, 2025b); Although the International Renewable Energy Agency (IRENA) provides a somewhat lower global weighted average for utility-scale (273 $/kWh), the investment costs in Europe and the United States are in the same range as the Danish values (International Renewable

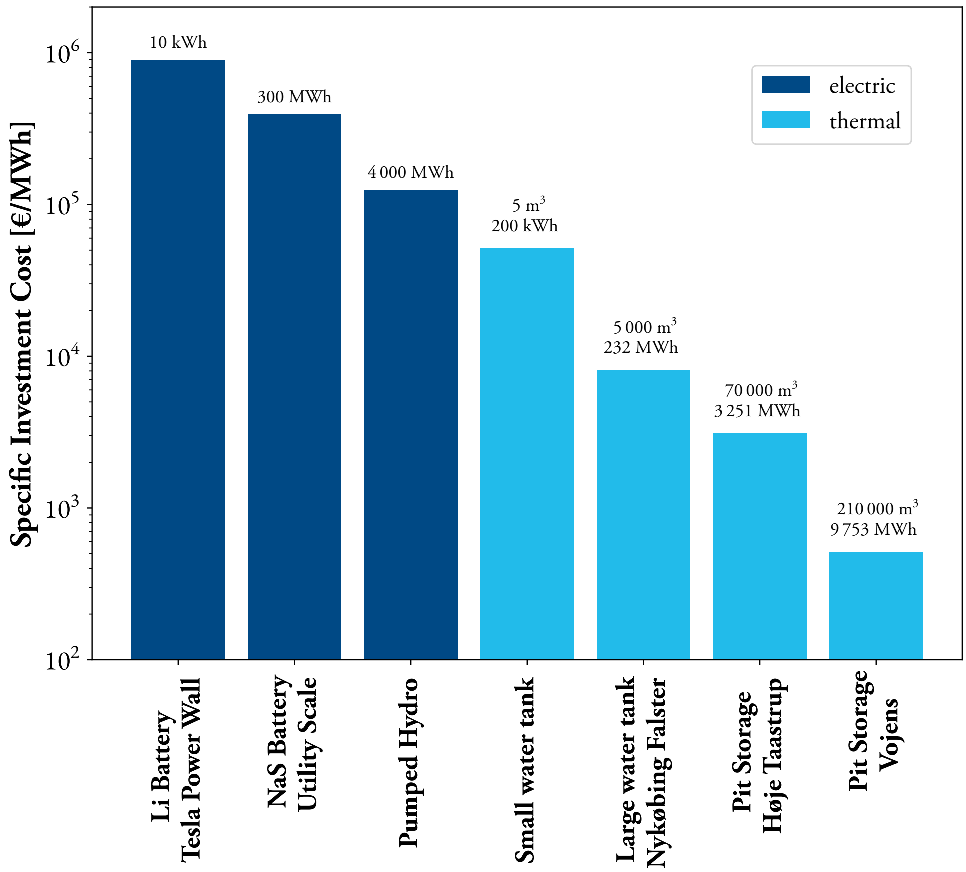

Figure 3.13: Specific investment cost of various types of energy storage. Various sources [71]

The smart energy system concept, further developed in Mathiesen et al. (2015), is facilitated by district heating equipped with thermal storage since its cost is considerably lower than

Energy Agency (IRENA), 2024, pages 145-148). Concerning pumped hydro, the International Renewable Energy Agency (IRENA) (2024, page 151) indicates that the global average investment cost was 149 $/kWh in 2023. In contrast, in Spain, Enseñat y Berea (2021) indicates investment costs ranging from 50 to 200 €/kWh, although recent projects and proposals show lower costs (Roca, 2019; Castaño, 2025; Ingeniería Pontificia, 2025), and in Norway, thanks to favourable conditions, investment costs ranging from 0,41 2008 NOK/kWh to 7,37 2008 NOK/kWh can be derived from Ingebretsen and Johansen (2014). Concerning thermal storage, the cost of a small water tank was retrieved from the supplementary material of paper IV of this thesis, the cost of Nykøbing Falster's new water tank stems from Arnholm (2020) and similar costs can be observed in the suplementary material of paper IV, and the cost of the two pit storages can be found in the Technology Catalogue (Energistyrelsen, 2025b). It must be noted that the different specific investment cost figures do not take into consideration the varying technical lifetimes across storage types; whereas a battery may be used for 30 years, the civil infrastructure of a pumped hydro storage can last over a century.

small-scale thermal storage and especially compared to electricity storage (Lund et al., 2016). An example of these flexibility benefits is shown by the Heat Roadmap Europe 4 project, which deduced that a decarbonisation strategy based on an expansion of district heating could enable a substantial reduction in peak power capacity in the electricity sector, and hence costs, compared to a conventional approach solely based on individual heat pumps (Paardekooper et al., 2018a). Another example is provided by research carried out by the University of Aachen and Fraunhofer, which shows that an expansion of district heating in Germany would bring about savings to the energy systems by, among others, reducing the costly endeavour of electricity grid reinforcement (Schwaeppe et al., 2022). Furthermore, district heating units, be they cogeneration plants or heat production plants, may provide ancillary services to the electricity grid such as frequency and or voltage control (Østergaard, 2006; Kortegaard Støchkel & Pedersen, 2017; Meesenburg, Markussen et al., 2020; Goodstein & Voldgaard, 2022; Zhang et al., 2022; Goodstein & Voldgaard, 2023).

This production flexibility can also be exploited in individual buildings as shown, among others, by Ingvarson and Werner (2008), Hedegaard et al. (2019) and Johra et al. (2019), either by taking advantage of the thermal inertia of the buildings or by adding specially purposed thermal stores. Furthermore, the potential for individual buildings to store thermal energy can be substantial as exemplified by Johra for the case of Denmark (Johra et al., 2024). Nevertheless, the storage capacity of buildings is time-limited, unlike large thermal storages [72] and reaping this untapped potential would entail a higher degree of complexity due to the significantly larger number of actors involved.

This increase in the synergies between sectors promoted by the Smart Energy Systems concept brings nonetheless a potential drawback: a significant rise in the system's complexity. This additional complexity may render the system more fragile, and disturbances in one sector, such as an outage of the electricity grid, would more easily propagate across sectors with probably unforeseen cascading effects in the rest of the energy system. In contrast, in the more simple and compartmentalised energy system of the past, disruptions in one sector could be more easily contained.

Moreover, this higher vulnerability to disturbances would not be confined to the technical domain. As shown by Summerton (1992) for the interaction of a district heating system with the wider social environment of Mjölby, the energy system operates within a much broader social context with which interplays in multiple levels. This wider social perspective

[72]This is exemplified by a comparison of the time constants of the two type of storages. According to Wigbels et al. (2005, page 31), the time constant is the ratio between the thermal capacity of a building and its thermal conductance and it represents the time it takes to a building for the indoor-outdoor temperature difference to drop to a third of the initial value (exactly to $1/e$). Ingvarson and Werner (2008) evaluated a series of Swedish buildings and reported time constants ranging from 100 to 600 hours, whereas a 5 000 m^3 water tank with a 300 mm mineral wool insulation and 2:1 height to diameter ratio, would have a time constant of nearly 11 500 hours (Calculations are derived from those presented in the document "Heat Losses of Thermal Energy Storage" of paper IV's supplementary material).

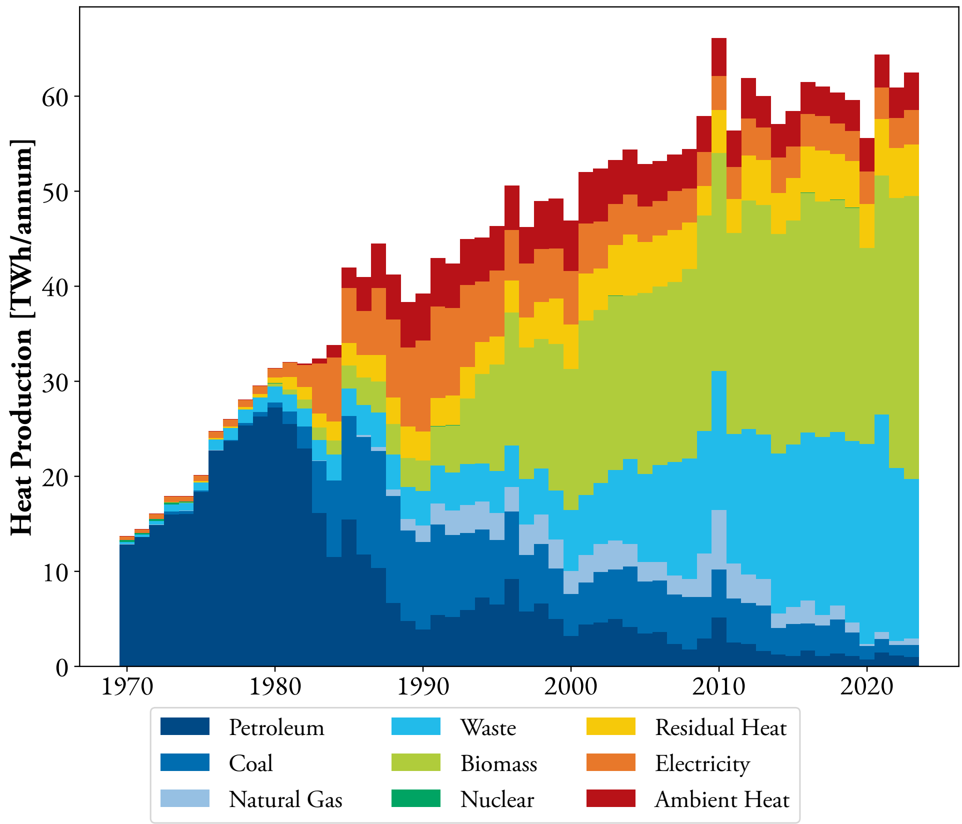

Figure 3.14: Gross [73] energy production in Swedish district heating systems according to *primary* energy sources. Various sources [74].

raises a critical question, to what extent do all countries possess the economic, education, technical or political resources to implement and sustain such a system.

3.4.4 Long term flexibility

A crucial characteristic of district energy systems is that they are *agnostic* concerning the heat and cold sources. *Id est*, they can transport any source of heat or cold, provided that they have an adequate temperature, in a similar manner to electricity grids. As Werner highlighted *"units come and go [...] but the network remains"* (Frederiksen & Werner, 2013a, page 437).

[73] Including distribution losses.

[74] The primary source has been the statistical series *Elförsörjningen*, electricity supply, continued by *El- och fjärrvärmeförsörjningen* in 1974, *Energi. el- och fjärrvärmeförsörjningen* in 1975, *Elförsörjningen och*

This feature allows a seamless transition between various heat sources with little or no impact on consumers as the operator pursues the changing aspirations of societies, such as addressing the climate crisis, economy, health concerns, security of supply, energy independence, and so forth. In the long history of a district heating system, the network may have been fed heat stemming from an oil or coal boiler, a combined heat and power plant, waste heat from a factory and lastly excess heat from a data centre training artificial intelligence algorithms.

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fjärrvärmeförsörjningen in 1976, *Elförsörjningen och fjärrvärmeförsörjningen* in 1980 and *El-, gas- och fjärrvärmeförsörjningen* in 1990, elaborated by *Statistiska centralbyrån*, Statistics Sweden, collected by Sven Werner and scanned by Helge Averfalk. Additionally, heating values were retrieved from Energikommittén (1967) in order to convert fuel use for the period 1970-1973.

Concerning the sources, the following remarks must be made. Firstly, *"residual heat"* refers to industrial excess heat and may include a certain electricity consumption for heat pumps operated by the industries. Secondly, *"electricity"* refers to the electrical input to heat pumps, electric boilers and circulation pumps, whereas ambient heat stems from heat recovered from the environment by heat pumps. Thirdly, *"waste"* primarily refers to urban garbage, regardless of its renewable nature. Fourthly, the published series contained a category denominated *"other"*, which was further broken down into narrow categories between 2004 and 2020. Based on this categorisation, it was possible to allocate this category to *"biomass"*, *"petroleum"* and extend these shares back to 1980. These fractions constituted, on average, 91,8%, 0,5% and 7,7% of the energy delivered, respectively, and lacked any significant trend. In addition, for the period 1970-1974, a significant fraction of *"other"* was assumed to have stemmed from the nuclear plant of Ågestaverket, according to production figures by Östman (2002) and was allocated to the category *"nuclear"*, and the remainder was assigned to *"waste"* based on detailed company figures from the annual statistics of *Svenska Värmeverksföreningen*, the Swedish District Heating Association. Fifth, peat was assigned to the category *"coal"*, since it was deemed as fundamentally non-renewable in human time scales and constitutes the first stage of coal formation. Sixth, *masungas*, gas from blast furnaces, was allocated to the category *"coal"* as it is a by-product of steel reduction with coke, biogas and landfill gas were assigned to biomass and propane and butane were assigned to petroleum. Seventh, *stadgas*, town-gas, was allocated to the cateogries *"coal"*, *"petroleum"* and *"natural gas"*, depending on the raw energy inputs for the gas works. The last available yearly statistics published by *Svenska Gasföreningen*, the Swedish Gas Association for the year 1969 (Svenska Gasföreningen, 1970) indicated that 38% and 62% of the energy input stemmed from petroleum (mainly *gasnafta*) and coal, respectively. However, only three gas works, Stockholm, Gothenburg and Malmö, still used coal by that time and only in the first one accounted for the majority of the town gas production. According to Stockholm's municipal archives (Agrenius & Spångberg, 1970; Blom & Spångberg, 1971, 1972; Blom & Tholson, 1973), the city transitioned rapidly to petroleum-based production and coal use was abandoned by 1974. For the period 1970-1974, it was assumed that the production shares among cities remained constant, and the transition towards petroleum paralleled Stockholm's; since this latter city accounted for 59% of the total town gas production, the potential error is minor. The period 1974-1990 is assumed to have been completely dominated by petroleum-based production, albeit natural gas was introduced in Sweden in 1985 (Mascherbauer et al., 2025) and blended with air to produce town-gas. Between 1990 and 2003, town-gas production was allocated to petroleum and natural gas based on production figures from the yearly *El-, gas- och fjärrvärmeförsörjningen*, and after this year, Eurostat's energy balances (European Commission, 2023b) were used with the same purpose (Transformation input - gas works - energy use). Eurostat's balance lacked data for the years 2011-2012, and these were allocated to natural gas following later years' energy use values and the final closure of petroleum-based town-gas in Stockholm (Svenonius, 2010). Finally, fuels have been treated identically regardless of means of conversion (Combined Heat and Power or Heat Only Boilers), and the same conversion efficiency was assumed for all fuels, since no fuel-specific efficiencies could be calculated based on the available data.

On an aggregate basis, the shift of energy sources over time can be observed in the production series from countries such as Sweden, depicted in Figure 3.14, Denmark (Johansen & Werner, 2022) or Lithuania (Jonynas et al., 2020). In the case of Sweden, it can be clearly observed that petroleum was the main source of heat until the 1980s, when the production mix began to diversify in the aftermath of the Oil Crises. Although a fraction of petroleum was substituted by imported coal, indigenous sources such as electricity, waste and biomass residues became the most widespread sources. In the future, higher competition among biomass uses will likely lead to a reduction in its use and a switch to other sources.

Electricity grids also share this feature, but unlike thermal grids, which can recover low-grade sources of energy, they present the *limitation* of requiring a higher quality of energy to be integrated. In this sense, a decarbonisation primarily based on individual heat pumps presents a certain lock-in effect since it prevents the future use of a low-quality heat source that may become available to society.

Chapter 4

Network costs

As highlighted in the prior chapter, district heating and cooling systems present an array of benefits for society. Therefore, at first sight, a layman could conclude that, given these advantages, all or most buildings ought to be connected to a district heating network, following the same pattern as in the electricity grid.

Nonetheless, the exploitation of these advantages necessitates the construction of a distribution network in order to transport the heat between producers and consumers. As with any civil infrastructure, the costs of these grids may vary significantly depending on local conditions, and, in some cases, their weight could cancel out the prior advantages.

This chapter explores the costs of district heating networks, their influence on district heating feasibility and presents a model used to estimate them in a simple manner.

4.1 The cost of distributing heat and cold

The cost of heat and cold distribution represents the cost of building, maintaining, and operating the network of pipes that delivers district heat and/or cold to the consumers. Although the two latter components are not negligible [75], the capital investment accounts for the largest share of the distribution cost.

[75] Frederiksen and Werner (2013a, page 524) indicate that the annual expenditures on network maintenance typically represent 1% of the initial investment. The other main expense, pumping, is also relatively small and, in the case of district heating, it contributes to the heat delivered by the system. According to prior work of this author, both academic (Sánchez García, 2018) and professional, pumping tends to account for less than 1% of the heat delivered; similarly, a study of Euroheat & Power across several European systems, reported pumping costs ranging from 0,3% to 1,8% of the supplied heat (Study Committee for heat transport and distribution, 1999b).

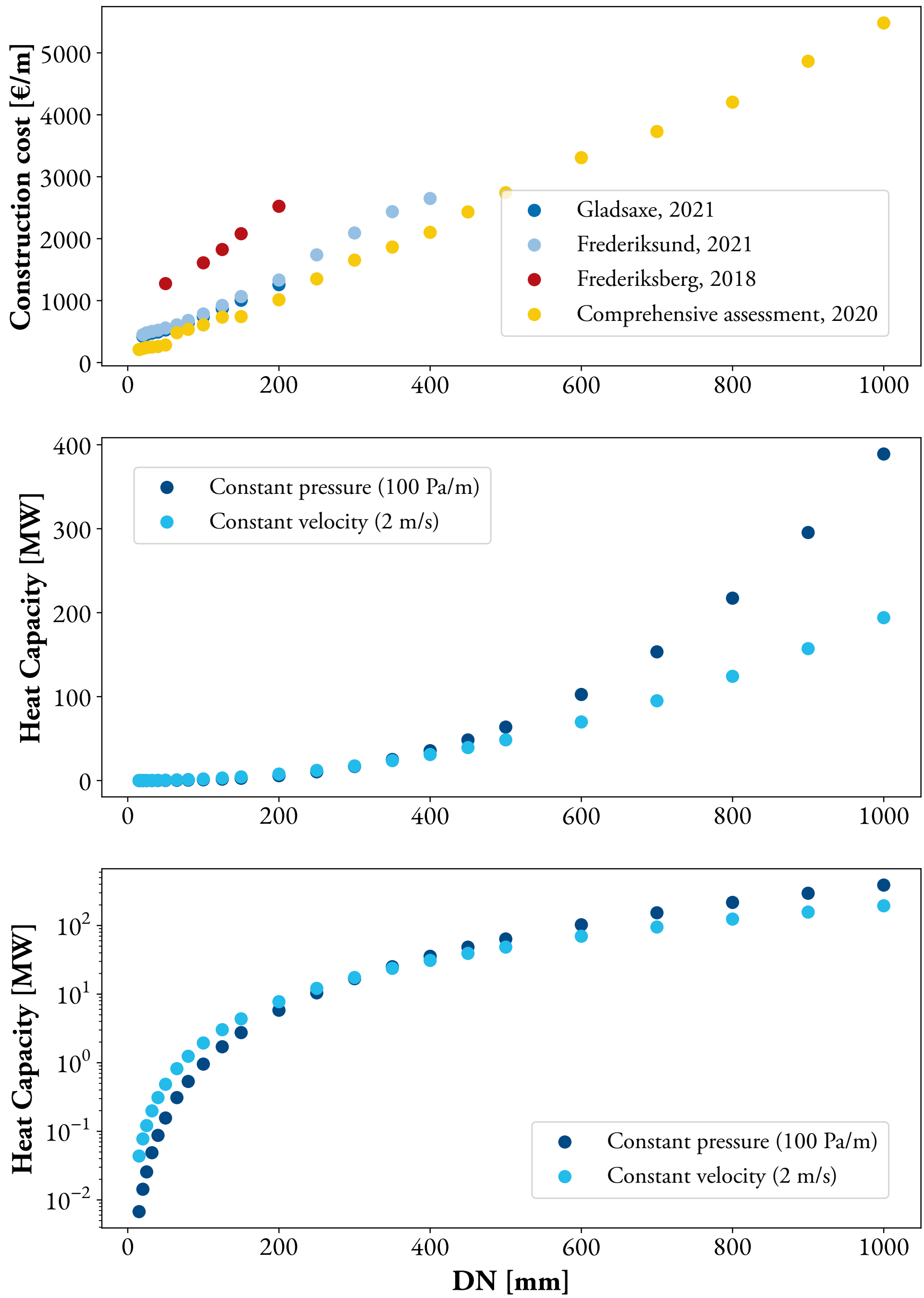

Figure 4.1: District Heating pipe construction costs and capacity as function of the pipe diameter [76]. Sources: Rambøll (2018, 2020, 2021a, 2021b) for the first graph. Own elaboration for the second/third graphs.

The network cost depends on a myriad of factors, such as the consumers' heat loads, temperature requirements, internal heating installations and location, the street pattern, the topography, the cost of construction materials, the cost of labour and so forth. However, despite all these compounding elements, it is possible to identify a crucial parameter for the cost of distributing heat: the concentration of the heat demand. From a qualitative standpoint, it is easy to appreciate the importance of this parameter. On the one hand, the more localised the heat demand is, the lesser length of pipe will be needed as consumers will be closer to each other. On the other hand, while the cost of installing a metre of district heating pipe increases linearly with the diameter [77], as shown in Figure 4.1.a, the capacity grows more rapidly [78], as illustrated in Figure 4.1.b or 4.1.c. Therefore, the specific cost, i.e., the cost per unit of delivered heat, will decrease with the diameter. Thus, in denser areas, the specific cost is likely to be lower than in sparser areas.

In geographic analysis, this concentration of the heat demand is usually measured as the land or ground heat density or, simply, heat density, which is the ratio between the heat demand in a given region and its corresponding land area, as indicated in Equation 4.1. It presents the main advantage that it is readily available once the consumers' heat demands are known and, in a simple manner, allows for discerning the areas with the lowest network cost. However, the land heat density presents some drawbacks for the estimation of the network cost as the following example illustrates; two sites with identical heat densities but different building distribution can lead to significantly different costs as the area where the shortest pipe is needed will deliver a substantially lower network cost [79]. Therefore, a parameter that simultaneously takes into consideration both the heat demand and the trench length will likely provide a much better indicator of district heating network costs. This parameter is the linear heat density, q_{Line}, as indicated in Equation 4.2

$$q_L = \frac{Q_s}{A_L} \tag{4.1}$$

$$q_{Line} = \frac{Q_s}{L} \tag{4.2}$$

[76] Note that the second and third graphs are built on the same underlying information.

[77] The linear relation between pipe diameter and installation costs has persisted across geographies and through time as can be observed in early references (Buck, 1968; Dafgård, 1979; Fjärrvärmebyrån i Västerås AB, 1986), as well as more recent ones (Study Committee for heat transport and distribution, 1999a; Svensk Fjärrvärme AB, 2007; Nussbaumer & Thalmann, 2014; AECOM et al., 2017; Dénarié et al., 2020; Rambøll, 2020). Economies of scale in civil works make up for the superlinear growth of pipe materials, resulting in an approximately linear overall trend.

[78] Were the water velocity to be constant, the capacity would grow with the square of the diameter ($\dot{V} = v \cdot A = v \cdot \pi \cdot R^2 \rightarrow \dot{V} \propto D^2$). Were the pressure loss to be constant as suggested by some guidelines (Frederiksen & Werner, 2013a, section 10.3.5; Phetteplace, 1995; Isoplus, 2011, section 2.1.3), the capacity would grow even faster, with the 2,6 power of the diameter ($\dot{V} \propto D^{2,6}$).

[79] This distinction is clearly illustrated in Nielsen (2014).

Where:

- q_L is the ground or land heat density [80].
- q_{Line} is the linear heat density.
- Q_s is the heat sold to consumers.
- A_L is the land or ground area.
- L is the trench length [81].

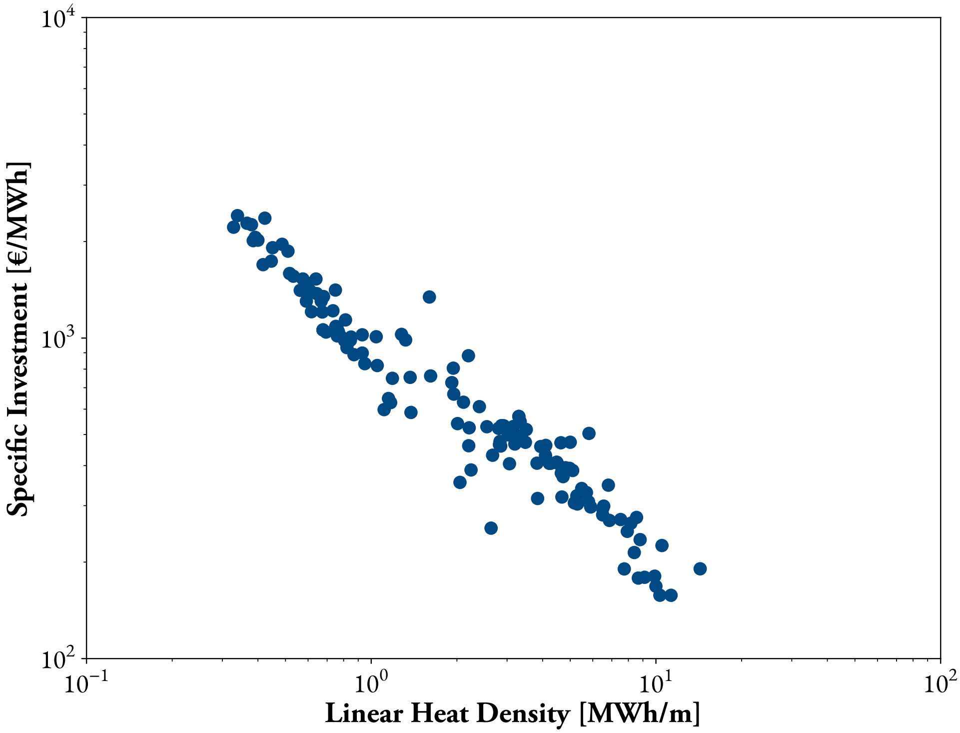

Figure 4.2: Specific investment [82]as function of the Linear Heat Density in 134 Swedish networks. Source: Own elaboration based on data gathered by Sven Werner and Svarc et al. (2023)

[80]Note that units have been intentionally omitted in this and further variable descriptions as any consistent set of units may be employed unless otherwise specified. This text mostly uses multiples of Wh for heat and SI units for the other variables. However, previous studies on the matter have solely employed SI units (Persson & Werner, 2011; Persson et al., 2019) and other units could be applied in principle. An important caveat concerns the empirical equations, where the provided units must be employed unless the coefficients are adequately modified.

[81]The terms trench length and pipe length are most often utilised as synonyms in the district heating field. However, in purity, the trench length only equals the pipe length when twin pipes are employed. Otherwise, the actual pipe length will be double the trench length. For the sake of clarity, only the term trench length will be used throughout this text.

[82]The specific investment is the ratio of investment and supplied energy. Note that the Levelised Cost of

The prior approximation to district heating network costs can also be deduced from empirical Swedish data gathered by Werner [83] and plotted in Figure 4.2 as well as from econometric analyses carried out on Danish district heating companies cost structures (Boscan & Söderberg, 2021). From Werner's data, we can deduce that the linear heat density is a good predictor of the network investment cost and, furthermore, that the capital costs vary widely and increase rapidly for low linear heat densities.

4.2 District Heating Feasibility

The overall cost of district heating not only stems from the district heating network but also includes the cost of heat production and connections to consumers. The costs for heat production may vary across locations, as some areas may have access to local, inexpensive sources, whereas other areas may have more limited options. However, as shown in the prior section, the costs of district heating can vary widely across locations. These cost disparities can drastically affect the competitiveness of district heating as illustrated in Figure 4.3. In high-density areas, network costs are low and district heating may be competitive with an individual solution, whereas in a low-density area, the benefits of district heating discussed in section 3.4 may not suffice to offset the costs of the distribution network.

In analyses of optimal pathways for heat decarbonisation, costs for individual and district heating solutions may be assessed at a *micro* or *macro* level, where the main difference lies in the aspects under consideration. In municipal heat planning or *micro* some aspects are usually disregarded as they usually lie out of the scope of the studies [84]. These excluded aspects typically comprise costs of electricity grid reinforcements for individual heat pump deployment [85] and energy system interaction effects, such as those described in section 3.4. These upstream impacts could justify the expansion of district heating beyond the *micro*

Heat distribution may be obtained by multiplying the specific investment by the annuity ratio, under the assumption of constant heat supply. A 30-year amortisation period and a 3% interest rate would render an annuity ratio of 5,1%, leading to costs ranging from 8 €/MWh to 123 €/MWh. All the investments have been determined with the same pipe construction costs, which leads to unrealistically high values in the least dense areas. These areas were undoubtedly developed with cheaper construction costs, which would have made them economically feasible.

[83] The same data is also plotted in Frederiksen and Werner (2013a, page 522), although, in this case, Werner based his investment calculations on the prior *Kulvertkostnadskatalog* (Svensk Fjärrvärme AB, 2007).

[84] Examples of this limitation may be found in Danish (Nielsen et al., 2020; Rambøll, 2023a, 2023b), German (Zipplies et al., 2023) or Italian municipal studies (Spirito et al., 2021), but also in assessments with a larger scope (Fallahnejad, Büchele et al., 2022; Ministerio para la Transición Ecológica y el Reto Demográfico & Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2023). Furthermore, the fourth paper included in this dissertation also has this *shortcoming*.

[85] For instance, in the sEEnergies project, Meunier et al. determined that covering 100% of the heat demand by means of air-source heat pumps could trigger investments of circa 1 200 € in rural grids and 170 € in urban grids (Meunier et al., 2021).

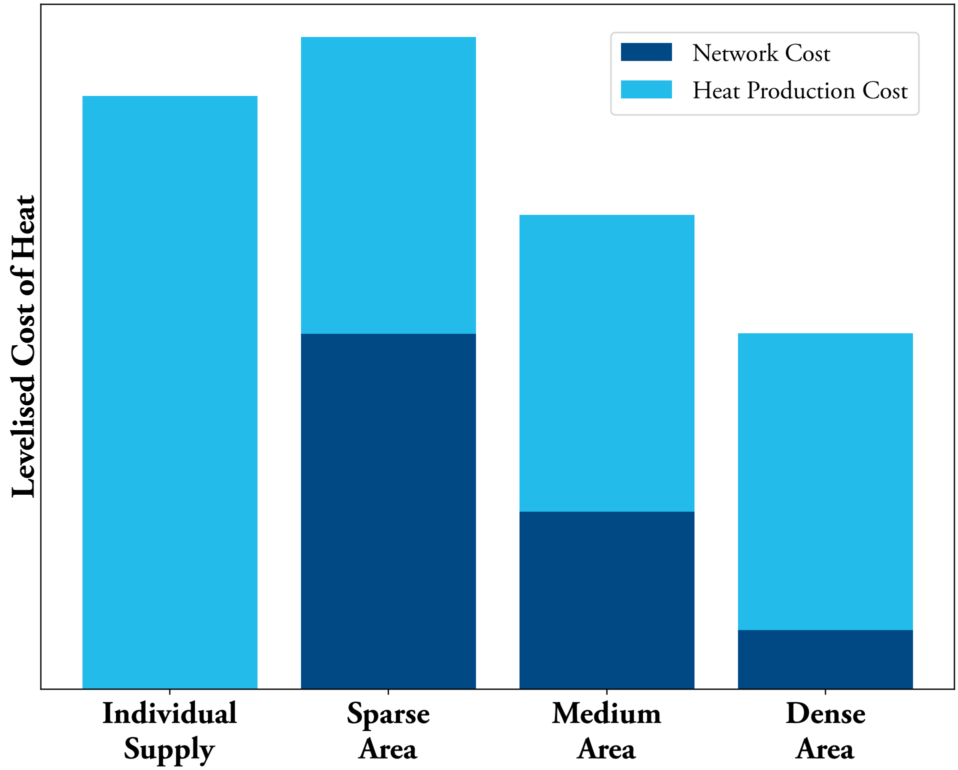

Figure 4.3: Cost comparison of individual heat supply and district heating in three different heat density areas. Source: (Persson & Werner, 2011).

least-cost solution, but they are unlikely to be strong enough to make district heating a suitable alternative when network costs are significant. Based on these considerations, we can infer that district heating feasibility in relation to individual heating solutions depends on network costs to a large extent.

4.3 The Persson & Werner model

Given the importance of the cost of district heating and cooling networks for their feasibility, Werner first presented a cost model [86] in Werner (1983) and Werner (1985), which was later developed in Werner (1997). Persson and Werner performed further improvements during the first chapter of the Heat Roadmap Europe saga (Connolly et al., 2012), and applied it

[86] Werner, in personal communication, highlights that the two early papers about distribution costs (Werner, 1983; Werner, 1985), were based on a different definition of linear heat density. They used heat supply rather than heat delivery (sold), where the difference lies in the network heat losses.

to several European countries (Persson & Werner, 2011). This model is derived below in Equation 4.3, where it can clearly be seen that the specific network cost is a function of the linear heat density and the unit cost of a district heating pipe.

$$I_d = \frac{I}{Q_s} = \frac{I/L}{Q_s/L} = \frac{I_u}{q_{Line}} \quad (4.3)$$

Where:

- I_d is the specific network investment, i.e., the quotient between the network investment and the delivered heat. It represents the necessary capital cost to deliver a unit of heat or cold at the consumer. If this parameter is multiplied by the annuity ratio, it is possible to reach the Levelised Cost of Heat (LCOH) for distribution.
- I_u is the trench-specific investment, i.e., the cost of a meter of district heating trench.

In a simple network with one sole pipe diameter, the specific network cost would be readily available by dividing the unit cost by the linear heat density. However, actual networks always consist of an array of different pipe diameters, each with various lengths. Thankfully, the construction cost of a meter of district heating trench is approximately a linear function of the pipe diameter, and it is possible to express the specific investment in an area as a linear function of the average pipe diameter, as demonstrated in Equation 4.4.

$$I_u = \frac{\sum_{i=1}^{N} L_i \cdot (C_1 + C_2 \cdot d_i)}{\sum_{i=1}^{N} L_i} = \frac{C_1 \cdot \sum_{i=1}^{N} L_i + C_2 \cdot \sum_{i=1}^{N} L_i \cdot d_i}{\sum_{i=1}^{N} L_i} = C_1 \cdot \frac{\sum_{i=1}^{N} L_i}{\sum_{i=1}^{N} L_i} + C_2 \cdot \frac{\sum_{i=1}^{N} L_i \cdot d_i}{\sum_{i=1}^{N} L_i} = C_1 + C_2 \cdot d_a \quad (4.4)$$

Where:

- L_i is the length of each trench stretch with the same pipe diameter.
- d_i is the pipe diameter of each trench stretch.
- d_a is the length-weighted average pipe diameter.
- C_1 and C_2 are the intercept and the slope, respectively, of the linear equation that relates the investment cost to the pipe diameter.

If Equation 4.4 is substituted into Equation 4.3, Equation 4.5 may be reached. Based on this equation, it is possible to determine the specific network cost in an area under study, provided that the average pipe diameter and the linear heat density are known.

$$I_d = \frac{I_u}{q_{Line}} = \frac{C_1 + C_2 \cdot d_a}{q_{Line}} \tag{4.5}$$

4.4 The effective width connection

Assuming that the installation costs of district heating pipes and the heat demand are known, only the trench length and the average diameter remain to be estimated. Based on these, it is possible to calculate the linear heat density and apply the model.

Unfortunately, neither the trench length nor the average pipe diameter are typically known before the network topology is decided and the pipes are sized. This difficulty led Persson and Werner to propose empirical correlations for the trench length (Persson & Werner, 2010) and the average pipe diameter (Frederiksen & Werner, 2013a, page 521; Persson & Werner, 2011) based on their study of Swedish district heating systems.

Considering the trench length, Persson and Werner took advantage of the effective width concept, which was introduced by Werner in a report to the late *Svensk Fjärrvärme*, the Swedish District Heating Association, (Werner, 1997). This parameter, w, is simply the ratio between the land area, A_L, and the trench length, L, as shown in Equation 4.6, and indicates the area supplied by a unit of trench length. Hence, the higher the effective width, the larger the area, and the more *effective* the network will be. Note that the term *width* simply refers to the fact that it is the width of a rectangle in which the other side is a unit of trench length.

$$w = \frac{A_L}{L} \tag{4.6}$$

Based on data gathered by Werner over his professional life as well as others (Netterberg & Isaksson, 2009), Persson and Werner related the effective width to a parameter of urban density, the plot ratio [87], ε, which is the quotient between floor area, A_f, and land area, A_L, as shown in Equation 4.7.

In Figure 4.4, it has been depicted the collected data by Werner and Netterberg & Isaksson as well as the proposed empirical equations. In this graph, the inverse of effective width, the unit length, L_u, has been depicted along with the effective width. The unit length

[87] Persson and Werner used the letter *e* for the plot ratio but the Greek counterpart ε has been preferred in this thesis in order to avoid any resemblance with Euler's number.

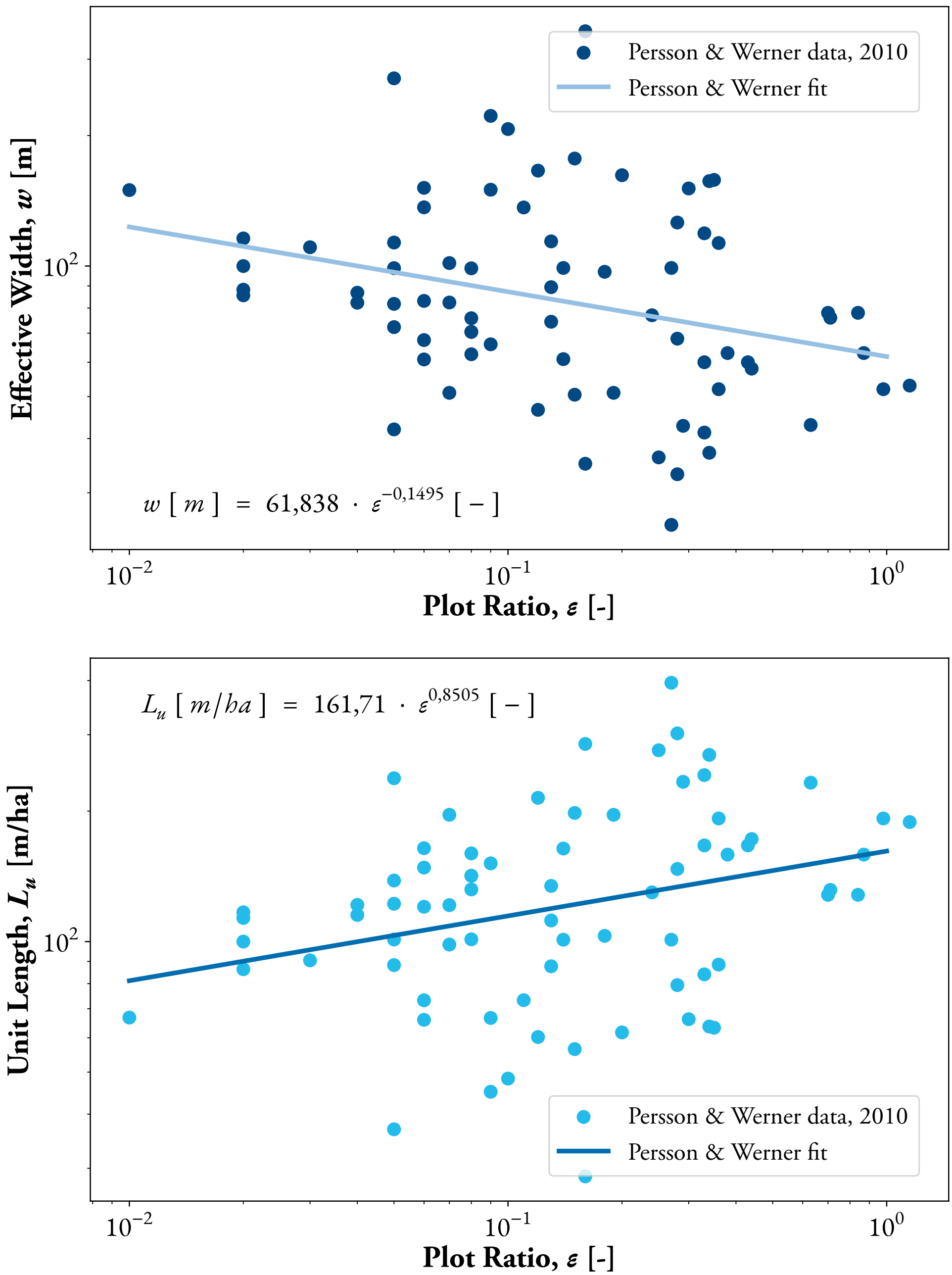

Figure 4.4: Effective Width and Unit Length as function of the plot ratio based on data presented by Persson and Werner (2011).

represents the required trench length per unit of land area, a concept that may be more intuitive to understand and will also be used later in this text. From Figure 4.4, it can be deduced that the effective width is higher in sparser areas, indicating that less trench length is required compared to more dense urban environments. Nonetheless, very few data points were collected in low-density areas, so the behaviour of this parameter in those areas remained unclear.

$$\varepsilon = \frac{A_f}{A_L} \tag{4.7}$$

$$L_u = \frac{A_L}{L} = \frac{1}{w} \tag{4.8}$$

Concerning the average pipe diameter, Persson & Werner presented another empirical correlation between the average pipe diameter and the linear heat density based on data

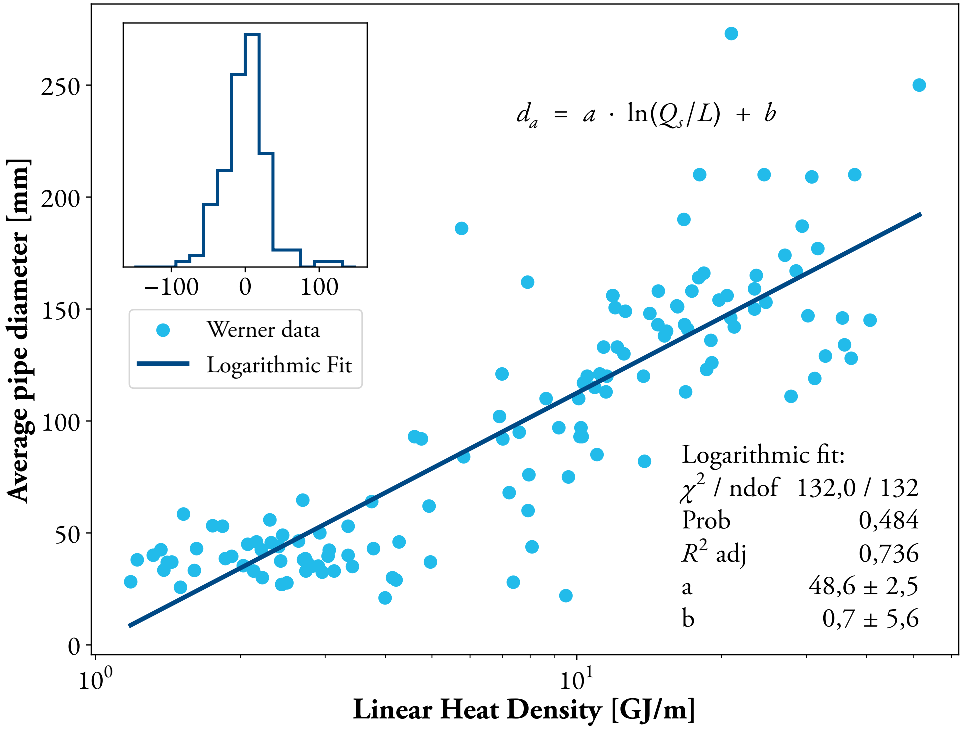

Figure 4.5: Relationship between linear heat density and average pipe diameter in 134 Swedish Networks. Source: Own elaboration based on data collected by Sven Werner.

from 134 Swedish district heating systems collected by Werner during the period 1972-2009. The data, along with the proposed equation, are shown in Figure 4.5.

4.5 Problem formulation

District heating suitability is determined to a large extent by the capital cost of the district heating network. In this context, Persson & Werner's model, alongside their empirical correlations for effective width and average pipe diameter, provide a data-lean and straightforward approach to obtain a first-order estimate of the capital cost, and hence suitability.

Notwithstanding their merits, the prior empirical expressions present a series of issues, which are discussed below. Firstly, the effective width equations presented by Persson & Werner are based on various sources, which, unfortunately, employed different definitions of land area. The first data used the concept *markarea* (Planverket & Statens energiverket, 1985), which did not include all the land area but solely the land lot and a fraction of the street area. On the contrary, later data, including that collected by Netterberg and Isaksson, used the entire land area. Moreover, the zones that defined the land area likely followed administrative boundaries rather than a homogeneous grid, leading to further inconsistencies as administrative limits tend to be somewhat arbitrary and include green areas, where district heating would not be deployed.

Secondly, Persson & Werner focused on medium-density areas since little data was collected on sparse areas. This shortcoming was likely motivated by the fact that district heating in Sweden primarily caters for multi-family buildings, and only a small fraction of single-family houses are supplied by heat networks (Werner, 2017a). Later studies such as Chambers et al. (2019) and Dénarié et al. (2021) have neither centred their attention on low-density areas. Therefore, sparse areas remain largely uncharted.

Additionally, only one study by Fattori et al. (2020) has explored the required trench length of service pipes [88] and generally, research has revolved around distribution pipes, which form the bulk of a district heating network.

[88] District heating network pipes are typically divided into two main categories, distribution and service pipes. Generally, distribution pipes follow the street and serve various consumers, whereas service pipes connect each consumer to the distribution network. Another distinction in some Danish low-density areas is that service pipes are usually built with flexible pipes, while the distribution system is constructed with conventional steel pipes. Furthermore, some large systems (e.g., Copenhagen, Aarhus, Fyn) also have a transmission system, which connects the various areas of a system, typically with higher pressures and, in some cases, temperatures (For instance the transmission network of Greater Copenhagen is operated by higher temperatures by different companies (Bergh-Hansen et al., 1987; Bach, 2014)). Nonetheless, the share of these pipes' trench length is very low compared to the others (less than 5% in Aarhus and Fyn).

Concerning the average pipe diameter, the equation proposed by Persson & Werner has been highly influential since its presentation and has been used in numerous studies (Gils et al., 2013; Hendricks et al., 2016; Lizana-Moral et al., 2017; Leurent, Da Costa, Rämä et al., 2018; Stegnar et al., 2019). However, it only addresses distribution pipes, which form the core of any district heating network, but does not provide any information on service pipes, which are also necessary.

Finally, only one study in the literature by Fallahnejad, Kranzl and Hummel (2022) has addressed the issue of model validation. Therefore, the question of to what extent the predictions of Persson & Werner's model are accurate has yet to be studied in depth.

4.6 Aim

Departing from the achievements of previous research on this topic, the work conducted in this thesis endeavoured to tackle its limitations. The objectives of this research journey may be summarised in the following questions:

1. What is the most appropriate grid size for studying the effective width parameter in a homogeneous grid?
2. What is the network's effective width in different urban density areas, especially in sparse areas?
3. What is the relationship between average pipe diameter and linear heat density for service pipes?
4. How does Persson & Werner's capital cost model, together with the empirical correlations, perform?
5. What is the potential for district heating in Europe based on Persson & Werner's capital cost model?

4.7 Methods

The work presented in this dissertation was based on an extensive geographic analysis of two large Danish district heating systems located in the municipality of Aarhus and the island of Funen, as well as several small areas around Denmark to be converted to district heating.

In Paper I, a geographic information system (GIS) of the central district heating system of Funen was constructed with information on the network's topology as well as the buildings' floor areas. This GIS, in turn, was utilised to analyse the required trench length for regions with different urban densities under various levels of resolution, i.e., using a homogeneous grid with varying sizes of cell (e.g., 1 ha, 4 ha, 9 ha, etc.). A similar expression to the one provided by Persson & Werner was used to fit the data and obtain new parameters, as well as to assess the influence of grid size on the coefficient of determination.

In Paper II, the geographic information system (GIS) developed in the previous paper was extended to the area supplied by Aarhus's municipally-owned district heating network [89]. Moreover, a layer including measured heat demands was incorporated into the model, enabling the determination of both land and linear heat densities throughout the municipalities.

Afterwards, the Funen data were exploited to fit new curves for the trench length of both distribution and service pipes. Furthermore, new expressions for the average pipe diameters of the two pipe types were also determined. These novel empirical expressions were then applied to the GIS containing the Aarhus network, permitting a comparison between the actual and predicted network costs. Finally, the same model was utilised in irregularly shaped new district heating areas in Denmark, allowing an additional validation of the model.

Paper III introduced several refinements into the capital cost model developed by Persson & Werner. Firstly, the model takes into account the evolution of the heat demand in a district heating area, improving the implicit assumption in Persson & Werner's model of constant heat demand over the entire lifespan of the infrastructure. Secondly, the effective width equations are modified so as to take into account the connection rate [90], this is the share of buildings connected to a network within its reach. Persson & Werner's model assumed all buildings to be connected, but in the absence of stringent regulation or strong price signals, this assumption was unlikely to be fulfilled. Thirdly, the paper introduces a minimum heat demand threshold in district heating areas, so smaller zones are not analysed further. This latter lack was not an inherent weakness of Persson & Werner's model but rather a simplification applied in the Heat Roadmap Europe and sEEnergies projects, which assumed all areas, regardless of size, to be viable for district heating development. Fourthly, each district heating area has a cost ceiling, so adjacent areas to district heating areas whose costs are above a certain threshold are not considered.

In addition to proposing these improvements, the capital cost model was applied to the entire European Union under two different heat demands scenarios, the "Best-Case" and the "BL2050" scenarios, based on a report published by the European Commission and the sEEnergies projects. Both scenarios estimate drastic reductions of the heat demand,

[89] In the municipality of Aarhus, the municipally owned network coexists with several minor consumer-owned networks.

[90] The connection rate is the share of consumers connected to a district heating network in those areas where a district heating network has been built. Note that the article uses the term *market share in district heating areas* rather than connection rate. Here, the latter concept has been preferred since market share may be used to indicate the fraction of all heat demand supplied by district heating.

45% and 33%, respectively, with respect to the current heat demand of circa 3 100 TWh. Furthermore, connection rates were assumed to increase in all countries towards 70-90%.

4.8 Results

This section presents the findings of the executed inquiries. For the sake of clarity, the outcomes are presented separately for each paper.

4.8.1 Paper I

The work in the paper I aimed to answer the first research question. A trade-off between grid size and accuracy was unveiled. On the one hand, coarser grids cause less dispersion in the correlation between the plot ratio, the independent variable, and the trench length, the dependent variable, hence higher coefficients of determination are attained. This behaviour is likely explained by the fact that larger cells do not adequately represent the urban fabric; in the lowest bound, a hectare only contains a few buildings for which many different trench lengths are possible. Larger cells tend to average these differences out, leading to less dispersion. On the other hand, larger cells generate model coefficients, which would deliver lower trench length estimates and hence, possible cost underestimations when the model is applied in small areas.

Additionally, it has been shown how another parameter of building density, the number of buildings per ha, is a better predictor of the trench length than the plot ratio, as the coefficients of determination are consistently higher, especially for the service pipes. This latter discovery may be explained by the fact that service pipes tend to have similar lengths, and each building typically requires a pipe.

4.8.2 Paper II

The investigation conducted in paper II sought to answer the second, third, and fourth research questions. Firstly, the behaviour of effective width was mapped over a wide range of building density areas, with particular attention to sparse areas, and new expressions were provided. In addition to the two parameters employed in Paper I, an additional parameter was explored, the Gini coefficient, which measures the inequality in the buildings' distribution within the grid cells. Nonetheless, the improvement brought by this supplementary predictor was somewhat limited.

Secondly, the average pipe diameter of both distribution and service pipes was related to the respective linear heat densities. Concerning distribution pipes, a similar expression to the one published by Persson & Werner was reached. However, although the correlation coefficients were statistically significant, a much higher dispersion was found. Moreover, the slope based on the Funen system was somewhat lower than Werner's, indicating that Danish systems may utilise smaller diameters. Regarding service pipes, the data presented a significantly different pattern; all service pipes had an average diameter of circa 20 mm in areas with very low linear heat densities (below 7 GJ/m), whereas above that threshold, service pipe diameters could range from 20 mm to 100 mm. This distinct behaviour may be explained by the fact that buildings in low-density areas have very similar heat demands and hence similar pipe diameters, whereas the nature of buildings in high-density areas is much more diverse, i.e., large and small buildings coexist in high-density areas.

In third place, the capital cost model proposed by Persson & Werner was applied along with the newly found empirical equations for effective width and pipe diameters in two distinct instances, a uniform grid in the city of Aarhus and irregularly shaped districts in Denmark. The validation in the municipality of Aarhus shows that the predicted specific investment costs vary widely with respect to the actual investment costs on a cell-by-cell basis. This is, if the predicted and actual costs are compared in one 1-ha or 16-ha cell, the difference can be substantial, albeit lower in the 16-ha cell. However, when cumulative investment or marginal costs were built, the predicted and the actual curves were very similar, especially those built with a 16-ha cell grid. The most likely explanation for this good correspondence between the cumulative cost/investment curves is that the aggregation that occurs in these curves likely evens out the differences in individual cells.

Concerning the validation in the Danish districts, the predicted results generally agreed with the actual costs, except for two districts, whose costs significantly deviated from the predicted. The fact that these districts expand over tens of hectares likely accounts for this good agreement.

4.8.3 Paper III

The research conducted in Paper III aimed to answer the last research question. Based on the Best-Case scenario, Paper III identified that 40% of Europe's heat demand in 2050 would be located in areas suitable for district heating, thereof 77% would be covered by these systems. The compound of these two factors would lead to district heating satisfying circa a third of the European Union's heat demand in 2050. Nevertheless, there were significant differences in the district heating potential among European countries, ranging from a nil share in Malta and Cyprus and a mere 4% in Ireland to 64% in Sweden, the country with the highest relative potential.

The realisation of these potentials would require an annual investment of 11 700 million € per year during the next four decades, although there was a wide range of variation across countries. The highest absolute investments would generally take place in the most populous countries: Germany, France, Italy and Poland would require 2 700 million, 1 500 million, 1 200 million and 1 100 million, respectively, but hefty investments would also be necessary in a medium country like Sweden which had a high potential for these networks (1 100 million €). In comparison to the Best-Case scenario, the BL2050 scenario would trigger a marginally higher share of district heating, 34% versus 31%.

4.9 Discussion

This section delves into the limitations of the analyses carried out, as well as puts them on a broader scope in relation to other research. It has been separated into two subsections as paper III has a different focus compared to papers I and II.

4.9.1 Papers I & II

Paper I and Paper II aimed to improve the model developed by Persson & Werner. An inherent property of the model is its simplicity and its ability to provide a first-order approximation to network costs. These characteristics can be advantageous for large-scale heat planning. For instance it could enhance the execution of the five-year comprehensive assessment on efficient heating and cooling [91] mandated by the Energy Efficiency Directive (European Union, 2023, Article 25). Nonetheless, the inherent nature of the model sets limits to its accuracy in small areas and hence, if more accurate results are desired, more detailed models such as that proposed by Nielsen (2014), or exhaustive hydraulic analysis as performed in Article IV ought to be conducted.

In paper I, an attempt was made to assess the trade-off between geographic resolution and goodness of fit, and it was observed that higher levels of aggregation were conducive to better fits between data and model. Nevertheless, was this improvement the result of an actual better correspondence between building density and trench length? Or, on the contrary, was it a spurious output consequence of the evening out that takes place when cells are aggregated into larger super cells?

The aggregation of cells into larger and larger *super cells* [92] tends to remove outliers as cells with very low or very high plot ratios and very low and very high trench lengths tend to be compensated by nearby cells with more average values. This fact points to the

[91] An analysis of the two rounds of comprehensive assessment allows to draw the conclusion that most countries do not explicitly calculate district heating network costs, and those who do in some cases, e.g. Spain (Ministerio para la Transición Ecológica y el Reto Demográfico & Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2023, section 5.2.3.1.), elaborate ad-hoc methodologies.

[92] The term *super cells* was used in Papers I & II to name the cells formed when aggregating one hectare cells.

second hypothesis. On the contrary, the fact that not only the goodness of fit but also model parameters change as a result of geographic aggregation, may indicate that higher geographic aggregation, i.e. larger super cells, do indeed reflect a better interrelationship. As reasoned in the paper, tiny *super cells* tend to capture an insufficient size of the urban grid and hence, cannot be expected to capture the required trench length to reach the buildings within the area under study.

Paper I and Paper II also aimed to map the behaviour of the effective width. Following prior research, this parameter was correlated to two different indicators of building density, the plot ratio and the number of buildings. This choice was motivated by data availability and by the fact that their definitions tend to be rather univocal, albeit the definition of floor area can be contentious, i.e. net or gross, total or heated. Nonetheless, this is an explicit limitation of the research, as the inclusion of other parameters could add explanatory power to the empirical correlations. Another parameter that could bear a higher correlation with the trench length is the street length, since most district heating pipes follow the street grid. However, even if it is a rather obvious metric at first glance, it becomes more problematic once a particular area is analysed in depth. Streets can be defined in Geographic Information Systems as consisting of multiple lines, and the practice of how streets are defined may not be homogeneous across countries. Software may alleviate this problem (e.g. several functions of the *sfnetworks* package developed by van der Meer et al. (2022)), but it is unlikely to solve all arising issues. Furthermore, the only open source GIS on a global level, OpenStreetMap, from which this information could be derived, is not fully comprehensive, as illustrated by the *Hotmaps* team for floor areas (Müller et al., 2019).

Another *self-imposed* limitation was the desire to use simple functional relationships between independent and dependent variables. Firstly, from a theoretical basis, a more parsimonious model is generally preferable to a model with multiple free parameters. Secondly, parsimonious models tend to have more predictive ability when extrapolating to different settings compared to an over-fitted model. Thirdly, it was reasoned that simple functions would render a more transparent model. Notwithstanding these advantages, during a statistics course, Dr. Troels C. Petersen suggested to this author the use of Machine Learning, as these techniques might be able to address the complexity of the relationships between density and effective width. This path was pondered but eventually relinquished, partly because of the aforementioned considerations, partly due to time constraints.

Two other limitations stem from the data used to tailor the model. The first data limitation comes from the fact that Danish urban patterns may differ from those of other countries, and hence, the extrapolation of empirical effective width correlations to other countries (e.g. Spain, Italy, France, Germany, etc.) could be fraught with danger. As the comparisons made in Article II illustrate, researchers from different countries have arrived at somewhat dissimilar results, and therefore, the application of the correlations in other contexts ought to be executed with caution. The second data-born limitation is that the model has been developed from actual networks in Denmark, and this begs the question of whether, embedded in the data, there is a survival bias. *Id est*, for a given urban density, do the fitted equations show the actual correlation between urban density and effective width for any given area? Or rather, do they show the correlations where practitioners have already deemed district heating to be feasible?

Concerning the other investigated functional relationship, the average pipe diameter as a function of the linear heat density, two questions can be posed. Firstly, Werner related the average pipe diameter to the linear heat density already in Frederiksen and Werner (1993), based on 32 district heating systems. However, this relationship lacks any clear theoretical grounds. For a single pipe stretch, it is possible to reach a power expression function of both length and heat delivered [93] $D \propto L^{\alpha} \cdot Q^{\beta}$ as shown in the supplementary material of paper IV [94] or by Trier et al. (2018, page 44) and Frederiksen and Werner (2013a, page 457), and a simple three pipe network leads to a complex expression involving products of delivered heat and trench lengths. Therefore, there is little basis for the assumption that pipe diameter must be related to linear heat density beyond the idea that networks with higher linear heat densities generally transmit more heat and hence require larger pipes. Despite this shortcoming, a statistically significant correlation can be found between the two variables in both the data gathered by Werner and by this author. Furthermore, relationships with other parameters (e.g. the product of trench length and heat demand) were investigated during the execution of this research, but only led to dead ends.

Secondly, as Figure 6 of article II depicts, the Fyn-based correlation estimates smaller pipes in areas with higher linear heat densities compared to the original expression by Werner. A similar finding can be reached were the data presented in Paper II's Table 1 to be correlated. Could this discrepancy be explained by the fact that Werner's data stems from entire systems rather than from neighbourhoods? Or, could this difference be attributed to different design assumptions? This is, the difference could be explained, among other reasons, if Swedish engineers conservatively assumed lower temperature differences in the past compared to more recent Danish projects. A more exhaustive analysis of Danish networks, as well as other countries [95] could shed light on this matter.

In addition, the extrapolation of pipe diameters to other latitudes could present some problems. The proposed equations use the linear heat density as this can be either available or be estimated with the aid of the effective width correlations. Nonetheless, pipe diameters are determined by the maximum flow circulating through the network, and a bijective relationship between both is only valid as long as temperature differences and capacity

[93] The expression actually depends on the flow, but under the assumption of constant temperature difference and constant capacity factor, delivered heat may be used instead.

[94] Document Determination of heat transmission costs.

[95] For instance, France's networks topology is currently open to the public (République Française, 2025), but unfortunately, it lacks information on pipe diameters.

factors remain similar. However, capacity factors tend to decrease [96] in milder climates (Frederiksen & Werner, 2013a, page 100) and therefore, the same delivered energy would trigger a higher peak power, and hence, a larger diameter, in Central and Southern Europe. In this sense, expressions based on Scandinavian data would likely underestimate the required pipe diameters in warmer areas.

4.9.2 Paper III

Paper III had the ambition of assessing the district heating potential in the European Union and tackling some identified drawbacks of prior research (e.g. Persson and Werner (2011) and Persson et al. (2019)). These limitations, among others, included the assumption of a 100% connection rate in district heating areas, constant heat deliveries over time or the assumption that district heating would be developed in any location regardless of size.

The hypothesis of 100% connection rate used in the Heat Roadmap Europe saga [97] was probably grounded in the experiences of Sweden and Denmark [98], where district heating systems have reached connection rates close to 100%. Notwithstanding, these high connection rates are perhaps unlikely to be reached in other areas that are less keen on collective solutions. Thus, the incorporation of variable connection rates and the adaptation of the effective width formulations represent an enhancement of the Persson & Werner model, and the obtained results are undoubtedly closer to reality.

Furthermore, earlier inquiries had assumed constant heat deliveries over time. However, a simple observation of the evolution of the heat demand in Denmark (Energistyrelsen, 2024a, page 36) or Sweden (Andreasson et al., 2009) highlights that specific heat demands have dwindled over time thanks to energy conservation measures. In a levelised cost of heat analysis, a reduction of energy deliveries increases the unit cost, on condition that outlays remain unchanged. This is actually the case, given that the network must be sized for the highest heat deliveries. Therefore, the earlier supposition overestimated district heating feasibility.

In this study, heat demands were derived from the European Commission's *A Clean Planet for all* strategy (European Commission, 2018a, 2018c), and heat demands were assumed to plummet from 3 128,8 TWh in 2020 to 2 088,7 TWh in 2050. These heat reductions are in

[96] A decrease in the space heating demand capacity factor is observed to occur in milder climates. If the shares between space heating, domestic hot water and heat losses remain constant throughout locations as assumed by Frederiksen and Werner (2013a, page 100), the total capacity factor will subsequently be lower too. However, in principle, a higher share of domestic hot water could make up for the lower capacity factor of space heating.

[97] And the sEEnergies project.

[98] For instance, district heating covers 98% of the heat demand of the entire municipality of Copenhagen (HOFOR, 2025).

line with Heat Roadmap Europe recommendations, and they are probably feasible in the better-off societies of Northern and Western Europe. However, in the poorer regions of the continent, they are perhaps too optimistic. As elaborated in section 2.1.1, in these areas, better economic conditions may lead to an increase in the buildings' heat demands despite the application of energy renovations and the effects of milder climates.

Finally, the performed investigation of Europe's district heating potential finds that 40% of the heat demand on the continent would be located in district heating areas, but due to connection rates of less than 100%, only a third of the heat demand would be supplied by these grids. Increasing the connection rates beyond this point would not demand substantial additional investments by district heating operators but could bring about system-wide benefits as those described in section 3.4.

4.10 Conclusions

The research conducted in Papers I, II and III aimed to improve the district heating network cost model developed by Persson & Werner and apply it to the European Union in order to estimate the potential for District Heating networks.

The work performed leading to the various publications has helped to elucidate the various research questions put forward in section 4.6

First, it was determined that there exists a trade-off between geographic resolution and effective width-building density correlation. A balance of both needs suggests that networks ought to be assessed with a resolution ranging from 16 to 25 ha.

Second, the behaviour of effective width was unveiled over a wide range of building densities and new equations for both distribution and service pipes were proposed. Furthermore, it was confirmed that the specific trench length presents an upper bound in high-density areas and a lower bound in very sparse regions.

Third, the logarithmic regression between linear heat density and average pipe diameter proposed by Werner was confirmed for distribution pipes, but the study of service pipes revealed a more complex relationship.

Fourth, the Persson & Werner cost model was validated under different topologies, a homogeneous grid of the city of Aarhus, Denmark, and irregularly shaped districts in the same country. Both analyses suggest that the model performs reasonably well in large areas regardless of shape, but in small-sized areas, it leads to significant error.

Fifth, the model was applied to the entire European Union under a series of conservative assumptions. Results indicate that district heating could deliver approximately a third of the EU's heat demand by 2050.

Chapter 5

Network configurations

As hinted before in sections 2.2 and 3.2.2, district heating and cooling systems may adopt different configurations. Conventional networks typically provide heat and/or cold at a sufficient temperature from a centralised production point, so only a heat exchanger or none are needed at the consumers' premises. On the contrary, other systems, such as those of Heerlen or Zürich, transport water at temperatures close to outdoor conditions, and the energy service is produced by the consumer with the aid of heat pumps. Intermediate configurations have also been proposed in which the temperature of the transport medium may be high enough to deliver low-temperature space heating, but a booster heat pump may be required for hot water preparation (Szabo, 2022).

Werner has analysed this issue in depth and proposed two different classifications for district heating and cooling systems (Werner, 2022). The first one is based on temperature levels for heating supply and divides networks into two main categories: warm networks and cold networks.

Where:

- Warm networks, the forward temperatures are at an adequate level to meet typical heat demands in buildings without any supplementary temperature boosting in the buildings.
- Cold networks, some additional temperature increase is required in the customer buildings to meet typical temperature demands.

Note that Werner's definition does not address the need for cooling, although it could be easily incorporated. Departing from the same principle of having the ability to deliver cooling directly or not, two different categories could be set, which, combined with the foregoing two, would render four possible combinations.

Nonetheless, the prior classification only focuses on system temperatures while neglecting other important aspects of district heating infrastructure. Therefore, Werner laid down another complementary classification, which is presented below:

- Classic, traditional district heating based on a two-pipe system.
- Modified Classic, slight alteration of the classic configuration with an additional pipe for separating bypassed warm water from cooled return water. Proposed by Averfalk and Werner (2018) and Averfalk et al. (2019) and implemented in Halmstad, Sweden (Norrström, 2021; Norrström et al., 2022).
- Multi-Level: system with multiple pipes supplying consumers with different temperature needs. Examples of multi-level networks are the system of SEMHACH in Chevilly-Larue, France (Faessler, 2015; Faessler & Lachal, 2017; SEMHACH, 2023) or the unrealised [99] GreenLab in Skive, Denmark (Andersen, 2019a, 2019b; Dyrelund & Bigum, 2020).
- Ultra-Low, two-pipe network that distributes low-temperature heat to be upgraded at the consumers' premises for delivering space heating and hot water. Depending on the source type, the temperature may suffice to deliver space heating. An early example of this configuration is the network in Oberland, Switzerland, which takes advantage of the drain water from the Furka railway tunnel (Rybach, 1995; Rybach & Wilhelm, 1995; Rybach et al., 2003).
- Cold Combined Heating and Cooling, similar to the Ultra-Low configuration, but decentralised heat pumps may provide both heating and cooling, using the network as source or sink or in concurrent production for matched loads. An example of this configuration is E.ON ectogrid in Lund, Sweden (Korsell & Ydén, 2021; Arnfalk, 2022; E.ON, 2023).
- Warm Combined Heating and Cooling, conventional system based on four pipes, two for a district heating network and two for a district cooling network. The district heating system of the 22@ neighbourhood in Barcelona exploits the residual heat from waste incineration to deliver both heating and cooling through a four pipe grid (Districlima, 2009; Mayol i Beltran, 2012).

Notwithstanding the particularities of each network configuration, the temperature level is perhaps the most defining characteristic, since it entails a drastic rupture with a long district heating tradition of production centralisation. Therefore, the dichotomy between warm and cold networks was the primordial interest of this research.

[99] Personal communication with Per Alex Sørensen, Plan Energi.

5.1 Potential benefits and drawbacks of cold networks

Even though there are early proposals for cold networks (Dutz & Jank, 1982), cold networks have gained research attention during the last two decades, and various reviews on their advantages have been published (Pellegrini & Bianchini, 2018; Buffa et al., 2019).

Buffa and Pellegrini have argued that cold networks present a series of advantages over conventional district heating systems.

Firstly, Buffa et al. claim that cold networks *"allow recovering low-temperature excess heat and include low-enthalpy RES"*. In similar terms, Pellegrini et al. posit that *"Traditional district heating and cooling networks are not suitable for this kind of smart integration, since the relatively high temperature of the water delivered in the network makes the system quite rigid and does not allow easy integration with renewables"*. Concerning the integration of renewable energy sources, Buffa et al. assume that cold networks enable *"higher interaction with the electric sector"*.

Secondly, both research groups also indicate that cold networks are *"bi-directional"* since they are capable of *"providing simultaneously both heating and cooling services throughout the year"* (Buffa et al., 2019). For Pellegrini, the issue of bi-directionality seems to be related to direction of water circulation in pipes, as they postulate that in conventional district heating *"the energy flux is mono-directional, from the central plant to the users and cannot be reversed"*, but cold networks *"also give the user the possibility of returning heat and/or cold to the cold ring: the cold ring thus performs a bidirectional energy exchange between the network and the users"*.

Thirdly, Buffa et al. allege as well that cold networks are modular, and hence they have *"flexibility and resiliency to a change of boundary conditions"*.

Fourthly, both groups of researchers defend that cold networks would have negligible thermal losses, even if employing uninsulated pipelines. Concerning the pipe materials, Buffa et al. argue that cold networks permit the use of polymeric materials.

A last advantage according to Buffa et al. is that the *"the ground and the network can be used as thermal storage"*.

A cold analysis of these alleged advantages may shed some clarity.

In the first place, cold networks can certainly integrate low-temperature renewable energy sources, as it has been effectively executed in Heerleen or Zürich. However, the exploitation of those low-enthalpy sources could have also been performed through a warm network, as Swedish networks have effectively carried out since the 1980s thanks to centralised heat pumps (Averfalk, Ingvarsson et al., 2017; David et al., 2017). Moreover, warm networks equipped with combined heat and power plants or heat pumps routinely interact with the electricity system and exploit price differences to their advantage thanks to ample thermal storage, so it is far-fetched that cold networks would have a higher interaction ability.

In second place, both groups of researchers apparently mix three very different concepts. The first is *"bi-directionality"*, which in purity ought to solely mean the possibility of reversal of water flows in the network. This *"bi-directionality"* cannot be called an advantage as in a warm network, water changes course on a routine basis, provided that the grid is meshed [100], and in a tree-shaped network with several production plants, water can also reverse course depending on the balance between demand and consumption in its different parts. The second concept is the possibility for the consumer to deliver heat to the network, acting as *"prosumer"*. *Prosumers* are neither a defining characteristic of cold networks as decentralised feed-in has been carried out in warm networks (Brange et al., 2016; Lennermo et al., 2019). The third concept revolves around the simultaneous provision of heating and cooling. Although this combined delivery of heating and cooling can also be conducted by warm networks, cold networks may indeed lead to lower costs since only a set of two pipes is needed, and distributed heat pumps may operate at higher efficiencies.

In third place, the modular feature of cold networks can truly be advantageous in some situations; for instance, if consumers are connected over a long period of time, investments can be delayed, leading to lower present values. Because of their centralised nature, warm networks typically incur higher initial investments.

In fourth place, cold networks naturally have very low thermal losses despite the use of uninsulated pipes due to the slight temperature difference between the circulation medium and the environment. This characteristic of cold networks could prove particularly beneficial in sparse areas, as in these environments low linear heat densities are conducive to high thermal losses (Werner, 1982; Bøhm, 1988; Heller, 2000; Mathiesen et al., 2019). Moreover, uninsulated pipes would likely be cheaper and easier to install, although the pipe cost does not dominate total installation costs (Svensk Fjärrvärme AB, 2007). However, the argument that cold networks can use polymeric pipes does not hold, as according to Johansen [101] plastic pipes for district heating began their development in the early 1970s (Bergh-Hansen et al., 1987, page 35) and new materials continue to be rolled out (Jorsal, 2022a, 2022b). An advantage of cold networks, though, is the extended lifespan of these pipes since high temperatures prematurely age polymeric materials.

In last place, the last advantage purported by Buffa et al. is the ability to store heat in the grid. Decentralised heat pumps can undoubtedly be steered to alter the network's temperature, but this technique is common in conventional district heating networks [102] (Frederiksen

[100] This is, the network has loops.

[101] Løgstør Rørindustri A/S, predecessor of Logstor, one of the large European district heating pipes manufacturers.

[102] A direct example of this strategy was observed by this author in Rønde Fjernvarme, Denmark, where the operators raise the forward temperature in advance of morning peaks.

& Werner, 2013a, section 10.6.7) and has also been object of research (Benonysson, 1991; Benonysson et al., 1995).

In addition to the prior benefits, Buffa et al. warn of several drawbacks that could jeopardise their implementation. On the one hand, they state that cold networks will experience larger flow rates due to the lower temperature difference between forward and return flows. These higher flows will, in turn, demand larger pipes and cause higher pumping costs. Nonetheless, pumping costs account for a small share of distribution costs as pointed out in section 4.1 and thanks to the lack of insulation, the outer diameter of a cold network pipe may not differ so much from the outer diameter of an *equivalent* [103] conventional district heating pipe. On the other hand, Buffa et al. alert about potential higher investment costs for decentralised heat pumps, albeit competition and mass production may drive down their price in a similar fashion to what gas boilers experienced during the 20th century.

In summary, cold networks benefit from lower heat losses and costs in the distribution network, higher modularity in their construction, and perhaps higher suitability for joint delivery of heating and cooling, but they may be chiefly hindered by higher investment costs.

5.1.1 The 5th generation conundrum

The Flexynets project introduced (Flexynets, 2015) and Buffa et al. popularised the term *"The 5th generation district heating and cooling"* following a previous paper by Lund et al. attempting to define the future characteristics of district heating (Lund, Werner et al., 2014).

Over the last decade, there has been considerable debate among the research community on whether cold networks constitute a new district heating generation or belong to the fourth generation.

On one side, Buffa et al., among others (Abugabbara, 2023), have argued that their characteristics make them distinctive enough to categorise them separately. On the other side, some authors such as Sulzer et al. (2021) claim that the definition purely based on temperature levels falls short, and several criteria must be taken into account for clustering district heating history. Furthermore, the category of fifth generation breaks the concept of generation as successive, rather than concurrent, stages in district heating evolution.

Analysing the definition of 4th generation district heating, a potential criticism can be raised; it is sufficiently vague to be applicable to almost any future technological development. In this sense, 5th generation systems can clearly be incorporated into 4th generation district heating and cooling.

[103] Capable of transporting the same heat power.

Nonetheless, and despite the ambiguity of Lund's definition, a fifth generation cannot be coetaneous with a fourth generation and the evolution of district heating technology is affected by more aspects than temperature.

Based on these considerations, this research came to the decision of avoiding the term *5th generation district heating and cooling* and rather focus on the implications of temperature levels and point of production.

5.2 Problem formulation

As presented in the introduction to this dissertation, district heating and cooling networks can contribute to tackling one of the major challenges that mankind faces today, the transition to an energy system based on renewable energy sources.

In the first part of this research, attention focused on the estimation of district heating network capital costs, further developing a simple model first presented by Persson and Werner. The application of this bettered model to the European continent also provided evidence that district heating systems can contribute to covering a significant fraction of Europe's heat demand.

Bearing in mind this huge possibility for district heating growth, and the different configurations it could take, it begs the question of what kind of district heating and cooling could turn out to be more advantageous.

Warm district heating has proven for the last century to be able to exploit the various benefits described in section 3.4. In addition, in dense areas it can lead to a lower heat cost as expounded in section 4.2. Nonetheless, cold networks could also exploit some of these benefits; e.g. they could contribute to increasing energy efficiency by recovering low-temperature heat, use buildings' and decentralised heat pumps to provide short-term flexibility and absorb different heat sources over time, paving the way for long-term flexibility.

Most of the literature focused on cold networks has analysed case studies, proposed optimisation methods or explored impacts of different system parameters, but little has been published on the economic benefits and drawbacks of cold networks in relation to warm networks.

5.2.1 Case study

In addition to the prior considerations on network configurations, during the execution of the Decarb City Pipes 2050 project, passionate discussions took place on the best path for the decarbonisation of the heat supply in the city of Bilbao, Spain.

The city lacked any city-wide district heating infrastructure, unlike most of the other project participants, and the population was mostly served by natural gas. In addition, the town's mild climate and the lack of tradition for these infrastructures in the country discouraged city officials and researchers of this decarbonisation option.

In this sense, it was also of interest to study the potential of warm and cold district heating and weigh them up against individual heat supply options.

5.3 Aim

Grounded on the previous considerations, it was decided to structure the research aiming to answer the following two questions:

1. Is a district energy solution economically feasible in a mild climate?
2. How do different district energy configurations compare to each other and other heating and cooling solutions in terms of cost-efficiency?

5.4 Scope

This section addresses the extension of this research, in terms of studied solutions, but also on the analysed metrics to compare them.

5.4.1 Heating and cooling solutions

As briefly presented before or in detail in Werner (2022), there are multiple network configurations, each with different variants. Therefore, it was decided to circumscribe this study to the following district heating alternatives:

I Classic configuration with warm network
II Ultra-low configuration with cold network
III Warm combined heating and cooling configuration with warm network
IV Classic configuration with warm network and building cold production
V Cold combined heating and cooling configuration with cold network

Concerning the individual heating solutions, the next alternatives were considered:

- Building and flat air-to-water heat pumps
- Natural gas boilers

The former selection considers the most adequate decarbonisation option, following the disquisition on section 2.2, and the most widespread heating solution in the city and Europe.

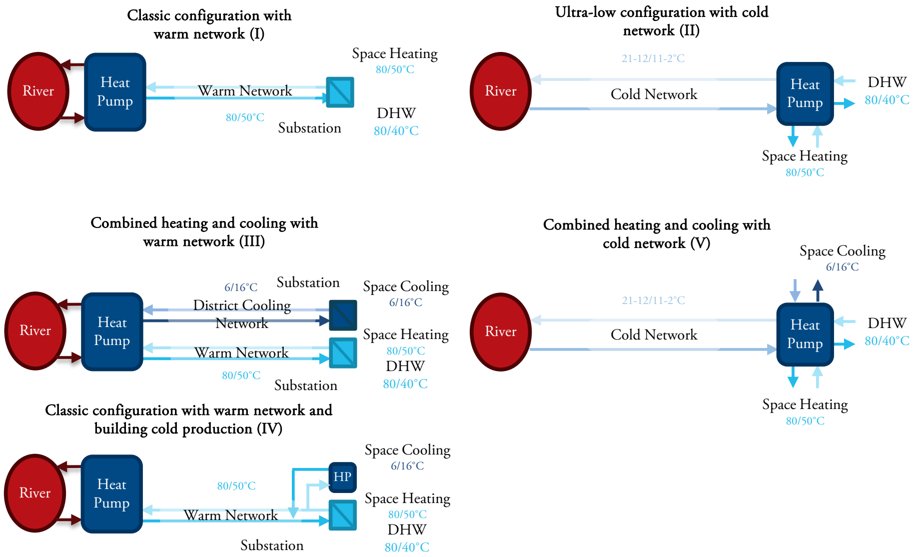

Figure 5.1: District heating and cooling configurations.

5.4.2 Comparison parameters

The breadth of this study was also limited to an economic analysis under the current framework conditions. In addition, all the energy system impacts discussed in section 3.4 were disregarded. This was intended to provide a conservative estimate of district heating feasibility, since the incorporation of those derivatives would favour thermal grids. Furthermore, no hard constraint on carbon emissions was imposed, implicitly assuming that the electric grid would eventually decarbonise. Nonetheless, carbon emission changes were calculated. Other relevant aspects, such as material exhaustion, exergy destruction, or second-order impacts, e.g., tax revenue change, were not considered.

5.5 Methods

Given the economic goals of this study, it was decided to employ the Levelised Cost of Energy (Aldersey-Williams & Rubert, 2019) as a means of comparison between alternatives. This parameter has the benefits of including all the outlays, taking into account the time value of money, and accommodating different technical lifespans, while delivering a neat indicator of the cost of a unit of energy.

Based on this premise, it was necessary to estimate the cost of installation and operation for the different alternatives under study.

Before any cost could be appraised, a Geographic Information System of the city's building stock was constructed, based on detailed information of the buildings' characteristics as well as measured natural gas demand at the postcode level. With the aid of this GIS, an analysis of the heat densities of the city, along with other parameters, such as the share of buildings with centralised systems and potential sources of heat, i.e. the river that crosses the city, led to the selection of an area for an in-depth study.

Concerning the solutions based on thermal networks, this estimation entailed the determination of the cost of the distribution networks, heat production units, as well as substations for the warm configurations. The thermal network sizing consisted of two main steps. In the first step, a heuristic algorithm was applied to reach the network's layout. In the second, pipe sizing was carried out according to detailed hydraulic modelling. On the contrary, mathematical programming was utilised for sizing the heat production units of all the district network solutions as well as building heat pumps. This optimisation technique enabled the determination of the combination of equipment sizes and dispatch with the lowest annualised costs.

Regarding the individual solutions, air-source flat heat pumps as well as gas boilers were sized without the need for detailed optimisation techniques as their capacity is directly driven by the maximum load, and no possibility for thermal storage was considered. In addition, the price of natural gas is not time-dependent, which renders any attempt at dispatch optimisation futile.

Besides the development of the different methods for cost estimation, an exhaustive analysis of potential data sources was conducted, aiming to obtain a representation as close to reality as possible.

5.6 Results

This section presents the results of the calculations performed in short, addressing the two research questions.

5.6.1 District heating feasibility

District-based solutions (configurations I and II) are generally more cost-effective than individual heat pumps in delivering low-carbon heat. These results are valid in both the base case, when a high discount rate is applied, and during the energy price spike of 2021-2022. However, the Ultra-Low configuration with cold network (II) at flat level is less economic than an individual air-source heat pump at all situations.

The generally higher costs of individual air-source heat pumps are explained by higher investment and operating costs. Higher investments are triggered by the somewhat higher specific investment cost [104], but mostly by the total installed capacity, which is substantially higher. This higher value stems from lower air temperatures, and hence lower COP values, but also from the same disadvantages of configuration II compared to configuration I, lack of diversity, more expensive heat storage, and only one heat supply source. Furthermore, higher running costs occur due to lower efficiency (air temperature tends to be lower than the river temperature during winter), and higher electricity costs at the consumer premises compared to available prices at higher voltage levels.

Unfortunately, the current principal form of heat supply, natural gas, is able to outcompete any of the low-carbon heating alternatives. The energy tax on natural gas merely reaches 2,7 €/MWh [105], compared to 28, 31 and 42 €/MWh in Sweden, Denmark and the Netherlands, respectively. This negligible energy tax fails to internalise the social cost of carbon, which is substantially higher [106]. Facing this challenge would require a pigouvian tax on carbon emissions (Pigou, 1920) and/or financial support for low-carbon technologies.

[104] The specific investment of individual air-source heat pumps is 18,7% higher than the district heat pump when $P_{el} \rightarrow \infty$.

[105] This figure stems from Eurostat's breakdown of natural gas price components (European Commission, 2023d) and results from the sum of Renewable and Environmental taxes. Given that the hydrocarbon levy on natural gas is only 2,34 €/MWh (Jefatura del Estado, 1992, 2013), the small difference must stem from other components, which are not *sensu stricto* taxes.

[106] Estimates of the social cost of carbon are hard to reach due to inherent difficulty of forecasting future costs due to climate change, but recent estimates by Rennert et al. (2022) point out to mean cost of 300 2020-$ with a 95% confidence interval of 100-600 for a 1,5% discount rate. Given specific carbon emissions of natural gas combustion at the time of elaboration of this study (Koffi et al., 2017), the mean social cost of carbon would translate into 72 $/MWh, which is nearly double the Netherlands' tax. Furthermore, research has pointed out that figures for the social cost of carbon have tended to rise over time (Tol, 2023), which indicates that this value is likely an underestimation. Finally, it must be noted that the Joint Research Centre (JRC) has slightly raised the figure for the specific natural gas emission factor after the elaboration of this study (Bastos et al., 2024).

5.6.2 Heating supply

Calculations show that cold networks (II) bring about an economic advantage concerning the distribution grid, but they also have higher heat production costs than warm networks (I). However, in the dense environment under study, the distribution grid accounts for a small fraction of the total expenditure and heat production represents the lion's share. This causes the classic configuration with warm network (I) to be able to provide heat at a lower cost than the Ultra-low configuration with cold network (II).

These results are consistent regardless of the point of supply, be it at a building or at a flat level, but also under different scenarios. The price shock experienced in natural gas and electricity prices would not alter the relative prices between solutions, and neither would a high discount rate. Only a large and far-fetched increase in thermal storage capacity at the buildings could put configuration II nearly on par with configuration I.

The Classic configuration with warm network (I) would also benefit from an expansion to a larger supply area, as this would allow a cost-effective heat transport from a nearby incineration plant. Thanks to the benefits of heat recycling and substantial economies of scale in heat transmission, the overall price of heat would slightly fall despite higher outlays for the distribution network.

The lower cost of heat distribution for cold networks is simply explained by the lower cost of uninsulated polyethylene (PE) pipes and their smaller outer diameter compared to district heating pipes, which ease their installation. This result confirms the hypothesis on pipe network cost put forward in section 5.1.

On the contrary, the lower cost of the classic configuration is brought by the advantages of centralisation and some of the benefits discussed in section 3.4. These can be broken down as follows: first, the centralised storage is not only cheaper in unit cost, but also not limited by space considerations at the buildings' technical rooms. Second, the presence of a back-up/peak gas boiler and thermal energy storage at the production plant enables a drastic reduction of installed capacity of the main production unit, a river-source heat pump, and a more flexible operation, taking advantage of the periods with lowest electricity costs. Third, the centralisation of production conduces to a reduction of the aggregated load thanks to diversification. Fourth, electricity costs are substantially higher for decentralised production at the building level due to higher electricity grid fees and charges [107] and electricity grid losses [108]. All of these economic advantages were only partially counterbalanced by lower

[107] Electricity charges cover renewable energies support, support for the insular systems (e.g. the Balearic and Canary archipelagos).

[108] The electricity consumer must purchase its gross electricity demand including the electricity grid losses. Thus, *caeteris paribus*, prices are higher at lower voltage levels. For a deep dive into these, the reader is referred to the supplementary material of paper IV.

specific costs for individual heat pumps, higher efficiency of heat pumps due to lower temperatures in domestic hot water production and substantially lower heat losses.

5.6.3 Combined heating and cooling supply

For combined production of space heating, domestic hot water and space cooling, the costs of warm and cold networks are virtually tied.

The Combined Heating and Cooling with warm network (III) would necessitate the construction of a district cooling system, which would account for the brunt of the extra cost of this solution. Expenditures for heating and cooling production would barely increase thanks to the synergies of concurrent operation of the centralised heat pump.

Conversely, the Combined Heating and Cooling with cold network (V) would experience an insignificant cost rise. The same pipe network and distributed equipment could be utilised for the cooling provision, and only a small increase in electricity expenses would occur.

Concerning the decentralised cooling production of configuration IV, it would not be cost-effective compared to the centralised production and district cooling network of configuration III. The lower efficiency and flexibility of the decentralised heat pumps would not compensate for the savings in the capital costs of the district cooling network.

5.7 Discussion

This section deals with the limitations of the study first and continues with a critical analysis of the results concerning the two research questions.

5.7.1 Limitations

This research aimed to assess the economy of various types of network configurations and alternative means of heating and cooling supply. Nonetheless, given its inherent nature as a case study, it presented some constraints to the extrapolation of its results.

The first limitation of the case study involves its location, the city of Bilbao, with certain characteristics that could make the results of the study not applicable under other conditions.

The climate conditions of the city are similar to other locations across Southern Europe, but considerably milder than in Northern and Central Europe. Similarly, the high density of the built environment is common in the South of the Continent, but substantially lower than in more northern latitudes, as pointed out by Persson et al. (2019). Nonetheless, it is the interaction between heat demands and urban density, which renders the heat demand density, that determines district heating feasibility to a large extent, as explained in Chapter 4. Surprisingly, these are similar across most European countries as Persson et al. highlighted. Therefore, some of the results pertaining to district heating feasibility and network configuration comparison may be applicable elsewhere.

There are also two other important factors that may deter the extrapolation of results. The first element is electricity and natural gas prices. According to Eurostat, Spain's industrial electricity prices tend to be in the middle of the range of all European countries (European Commission, 2023c) and household natural gas prices are rather similar (European Commission, 2023f) to the European average, albeit typically slightly higher. Therefore, given these price similarities, results may be generalised to other European countries to a certain extent. The second element is that a substantial fraction of buildings in the city does not have centralised heating and hot water systems, but rely on flat-level equipment. This widespread feature has far-reaching consequences on the ease of district heating deployment. Not only does it constitute a higher burden on the district heating developer and local administration, but it is also a more costly endeavour. However, results have been broken down by heating type, so it would be rather straightforward to extrapolate them to other locations with different building stock composition.

Furthermore, regulations and economic incentives have substantial effects on district heating development. European directives and regulations set a common framework among EU Member States, but national legislation may differ. Given that district heating in Spain lacks any kind of specific regulation and so far, a laissez faire approach has been followed (Billerbeck et al., 2023), results may be deemed somewhat on the safe side of district heating feasibility, and may be favourably extrapolated to other locations with more stringent policies in force [109] and/or higher economic incentives.

A second important limitation lies in the set of conditions studied. Rather than analysing a broad range of parameters such as Meesenburg, Ommen et al. (2020), who assessed various geographic circumstances, Zarin Pass et al. (2018), who addressed the impact of a range of heating and cooling shares or Guðmundsson et al. (2022), who approached diverse source temperatures, this evaluation has focused on a single area. Although the sensitivity analysis attempts to address this drawback, it falls short of fathoming the abyss of possible conditions. In this sense, it would be relevant to chart the unexplored constellation of combinations of demand densities, proportion of heating and cooling and system tempera-

[109] For instance, Italy, which otherwise presents similar conditions to Spain, has obligations to make buildings that fulfil certain conditions district heating-ready (Presidente della Repubblica, 2005, Article 4.24; Presidente della Repubblica, 2009, Allegato D.6 & Annex I.13). These requirements would facilitate the rollout of district heating networks.

tures. This exploration would unveil under what conditions the different configurations would be more economically sound.

Furthermore, due to time constraints, several aspects of interest could not be studied in due depth.

On the one hand, the potential expansion of the district network to a larger distribution area only addressed the Classic Configuration with warm network (I), and did not study the potential economic impacts for configurations (II-V). In these conditions, the exploitation of the city's high-temperature residual heat sources enabled a reduction of the LCOH for configuration I despite higher network costs. If this heat were to be used in configurations (II-V), several questions may be raised: What would be the adequate temperature levels for the cold network so that COP improvements overcome the increase in network heat losses? Would it be economic to deploy an absorption chiller to deliver cooling, either in a centralised manner, such as in configuration (III) or in a decentralised way, such as configuration (IV)?

On the other hand, the alternative means of heating and cooling supply, heat pumps and natural gas boilers, were circumscribed to the provision of heating, and the delivery of cooling was neglected. Given the growing importance of cooling, the evaluation of heat pumps for the dual yield of heating and cooling would be of interest. Could, in this case, heat pumps outcompete network-based solutions?

Finally, the scope of this assessment has been rather narrow, since only a few techno-economic aspects were studied. Setting aside important issues such as social acceptance [110], the analysis deliberately ignored important technical matters.

In the first place, even from the micro perspective taken, the effect of distributed heat pumps on the low-voltage electricity grid may be relevant; as other research focused on Spain has pointed out (Mascherbauer et al., 2025), the rise of heat pumps and electric vehicles would likely trigger a grid reinforcement, and hence higher electricity distribution costs. These extra costs would probably make individual solutions even less economically appealing.

In second place, most of the analysed heating and cooling options involve the coupling of the heating and cooling sector with the electricity sector, with substantial upstream consequences as highlighted in section 3.4. However, none of these impacts have been taken into consideration. Given the flexibility that Thermal Energy Storage (TES) grants to district-based solutions, it is likely that bearing in mind these upstream impacts would discourage the adoption of individual heat pumps further.

[110] As an example, citizens in the nearby town of Vitoria-Gasteiz considered the obligation to connect to a district heating network the lesser evil to be able to receive European aid for energy renovation (Vivienda y Suelo de Euskadi, 2020, page 11).

In third place, Life Cycle Assessment, such as that carried by Fröling et al. (2004), Fröling and Svanström (2005) and Persson et al. (2006) on district heating distribution networks or more recently by Olsson (2021) on the new PE-RT pipes developed by Logstor (Jorsal, 2022a, 2022b), can incorporate important information beyond pure economy. Following the work by Bartolozzi et al. (2017) and Leman (2024), the utilisation of Life Cycle Assessment would enable a better comparison between heating and cooling solutions.

In fourth place, the use of exergy analysis also presents advantages over purely energy flows since it takes into account the energy quality (Gong & Werner, 2015). Unfortunately, its use in district heating research has been scarce (some examples are provided by Li and Svendsen (2012), Gong and Werner (2015), Zarin Pass et al. (2018), Topal et al. (2022) and Li et al. (2023)), and to the best knowledge of this author, no district heating analysis has included the exergy of materials (Wall, 2009; Valero-Delgado et al., 2010; Michalakakis et al., 2021). The application of comprehensive exergy assessment over the different district and individual heating and cooling forms could shed light on their long-term sustainability in a complementary manner to the Life Cycle Assessment.

5.7.2 District heating feasibility

As mentioned in section 5.6, low-carbon technologies would fail to displace the predominant heat supply option, natural gas, due to the lack of internalisation of the externalities caused by green house emissions.

Unfortunately, Spain, along with its southern European counterparts and Poland, has one of the highest opposition rates against fuel taxes in Europe (Büchs et al., 2024). According to Büchs et al. (2024), the higher levels of social deprivation and low trust in these countries are the main factors for explaining this higher hostility towards carbon taxation. Similarly, Furceri et al. (2023) indicate that income inequality is a pivotal element for the backing of carbon taxation, and the country presents some of the highest income inequalities on the continent (European Commission, 2025i). This opposition to a Pigouvian tax on carbon could perhaps be overcome if the country adopted some form of revenue recycling such as the the withdrawn Canada's carbon rebate (Winter et al., 2023). This carbon check would turn the distributional effects from proportional, as research has documented in Spain (Labandeira-Villot & Labeaga-Azcona, 1999; García-Muros et al., 2017), to progressive.

Simultaneously or alternatively, financial support or other policy mechanisms could be enacted so as to change the relative prices between low-carbon solutions and conventional heating options. An example of these schemes is the French "*Fonds Chaleur*" (Leurent, 2019; Agence de la transition écologique (ADEME), 2024), and another successful example consists of the long-term and favourable loans provided by the Danish Municipal Bank *KommuneKredit* (Johansen & Werner, 2022; Rambøll, 2022).

5.7.3 Network comparison

Concerning the distribution network costs, the ultra-low temperature configuration with cold network (II) gives rise to lower expenditures than the classic configuration with warm network (I). More generally, this result is likely to remain valid under most prevailing conditions with two possible exceptions as pointed by Sánchez-García et al. (2022). In the first place, high temperature differences in configuration I could reduce the pipe diameter sufficiently to make up for the higher specific cost of preinsulated pipes. In second place, low economic savings when using uninsulated piping could nullify the cost advantage of configuration II. Despite the PE pipes themselves being substantially cheaper, civil works are preponderant in the total installation costs (Svensk Fjärrvärme AB, 2007; Svarc et al., 2023) and civil works do not differ so much between both pipe types, so a small cost difference between insulated and uninsulated pipes is not far-fetched.

Beyond construction costs, the features of the pipe network also affect the distribution heat losses. As shown by Werner (1982) and Bøhm (1988), heat losses fundamentally depend on the linear heat density and distribution temperatures. This is, *caeteris paribus*, distribution heat losses are higher the lower the density is and the higher the transport medium temperature is. Thereby, in low-density areas, the ultra-low temperature configuration (II) is bound to become even more economically sound, as negligible heat losses prevail, whereas they become prohibitively high for the classic configuration (I).

In the studied case, network costs constitute a small fraction of the total costs, which are dominated by heat production. Once all the outlays are taken into consideration, the economic benefit of city-wide centralised heat production becomes apparent, and the classic configuration with warm network (I) is able to deliver heat in a more cost-effective manner than the ultra-low temperature configuration (II). However, in sparser areas, the network outlays (Sánchez-García et al., 2023) and heat loss (Mathiesen et al., 2019) may rise to the point where the lower heat production expenditures of warm district heating (I) do not offset its higher piping disbursements becoming unfeasible, while a cold network (II) may still be an economically sound solution. In very sparse areas, individual heating solutions (e.g. individual heat pumps) would likely be advantageous as their cost is *not* sensitive to heat density [III]. Conversely, a higher density would also lead to a reduction in the network expenditures, which would render the classic configuration with warm network (I) even more economically competitive.

As presented before, the concurrent supply of heat and cold in configurations III and V has a cost levelling effect, which is explained by the substantial additional disbursement of building a parallel district cooling network. Similar to a district heating network, the specific cost of a district cooling network would fall as the cold density rises and vice versa.

[III] Electricity grid costs are dependent on density as shown by Energistyrelsen (2025c) for Denmark. However, these differences may not be reflected by the rates.

Therefore, the warm combined heating and cooling configuration with warm network (III) would likely deliver a more competitive service in high-density areas as the specific costs of the district heating and district cooling pipe networks drop. On the contrary, the cold combined heating and cooling configuration with cold network (V) would shine in low-density areas, as only one pipe network is required for the supply of heating and cooling.

Besides the direct economic aspects analysed in this study, the warm district heating options (I), (III), and (IV) would also benefit from the advantages presented in section 3.4. These include the rise of structural energy efficiency when recycling industrial residual heat, protecting jobs through additional revenue streams in the affected industries [112], and short and long-term energy flexibility. The short-term flexibility is exemplified in the production curves of this case study, where a higher production variation occurs in the warm configurations (I and III) in response to electricity prices.

On the contrary, a cold network (either the Ultra-Low configuration with cold network (II) or the Cold Combined Heating and Cooling configuration with cold network (V)) could lead to lower costs were the development of the network to be executed over a number of years, a scenario not addressed in this research. In these circumstances, the deferral of heat production investments could bring about a lower net present value and, hence, a lower levelised cost of heat, especially when high discount rates are applied. This situation is more likely to arise in new areas under development (where new buildings are gradually erected) or in an existing neighbourhood when a high connection rate may not be rapidly achieved.

Finally, considerable effort was dedicated to attaining representative cost data for the city. However, the costs of warm (I, III, and IV) and cold district heating (II and V) have likely been overestimated and underestimated, respectively. First, the specific investment costs of small water-to-water heat pumps are substantially lower than those of utility-scale heat pumps. This apparent paradox may be explained by heat pumps lacking clear economies of scale, as is the case for natural gas boilers, by the substantially lower Spanish labour costs (European Commission, 2023e) or by unaccounted costs in Spanish prices for water-to-water small heat pumps. This latter potential explanation may be backed by the fact that the total costs of district heating substations from actual projects are higher than for water-to-water heat pumps, despite substations being simpler apparatuses. Second, the costs for conventional steel preinsulated pipes have likely been overestimated, as similar projects in a nearby region have been more economical.

[112] This issue may be especially relevant in the Spanish context, characterised by structurally high levels of unemployment (European Commission, 2025k).

5.8 Conclusions

This study aimed to answer two research questions: whether district heating is economically viable and how district heating solutions compare to each other and other heating alternatives economically. A comprehensive analysis of the levelised cost of energy in an area of the city of Bilbao, Spain, was conducted to answer these questions.

Concerning the first research question, district heating solutions are economically viable in a high-density urban environment characterised by a mild climate when compared to individual heat pumps. However, unless present and future costs for climate change are internalised, neither district heating nor individual heat pumps are able to displace the incumbent fossil heating solution, natural gas.

Regarding the second research question, the classic configuration with warm network (I) is more cost-effective than the ultra-low temperature configuration with cold network (II). This result remains valid under a set of conditions, with high electricity prices, with a high discount rate, and especially if the system is expanded so that industrial waste heat can be recovered by the system. However, were the district networks to deliver cooling, the warm combined heating and cooling configuration with warm network (III) and the cold combined heating and cooling configuration with cold network (V) would bear similar energy costs, albeit slightly lower for the former.

Chapter 6

Concluding remarks

This thesis has addressed the imperative societal demand of decarbonising the heating and cooling sector by studying various aspects of district heating and cooling systems. Among existing options for decarbonising the heating and cooling supply, this technology could facilitate the decarbonisation goals more cost-effectively than the direct rollout of individual heating solutions. Still, it currently has a low penetration in the European context and it is unclear what network configuration would be more appropriate for future schemes.

On the one hand, research focused on district heating network costs, as these are critical for assessing the potential of district heating in Europe. The network capital cost model developed by Persson & Werner was improved and validated based on extensive geographic analysis of existing networks in Denmark. Based on these investigations, it was deduced that Persson & Werner's model performs well in large areas, but its accuracy drops in very small areas. Furthermore, the model was applied to the entire European Union in order to estimate the potential for district heating. It was assessed that district heating could cost-effectively provide a third of the heat demand by 2050.

On the other hand, this thesis addressed the costs of several configurations of district heating and cooling networks, broadly classified as warm and cold networks. Compared to conventional district heating or warm networks, where all the heat is centrally produced at the required temperatures by the consumer, in cold networks, a fraction of the heat demand is provided at the consumers' premises by means of heat pumps. These two main types of networks were contrasted for both the supply of heating and the simultaneous delivery of heating and cooling through a case study in the city of Bilbao, Spain. From this analysis, it was deduced that warm networks are most cost-effective when heating is the only service, but both network configurations reach similar costs when both heating and cooling are provided. Another finding was that no low-carbon heating and cooling alternative is likely to displace fossil fuels unless the social cost of carbon is internalised in the price.

Chapter 7

Future work

This chapter delves into possible extensions of the work conducted in this thesis, as well as other ideas which have not been possible to explore.

7.1 Network cost modelling and configurations

In sections 4.9 and 5.7, the limitations of the performed research were addressed. Future work could address these shortcomings and study improvements to the Persson & Werner model and the benefits and drawbacks of warm and cold networks in various circumstances and from several standpoints.

7.2 Other district heating research

Besides the research conducted in this thesis, which focused on district network modelling, other aspects of interest were not possible to address due to a lack of funding and time.

7.2.1 Night set-backs

Night set-backs are a feature of heating system operation in many European countries, as briefly mentioned in section 3.4.3 and the supplementary material of paper IV. They were traditionally advocated since they allowed for a reduction of space heating demand in poorly insulated buildings. In fact, in some countries, such as Italy, they are even compulsory (Presidente della Repubblica, 2013, Article 4). However, they are detrimental to district heating operation. Not only do they oblige to oversizing the distribution network, but they are also one of the causes for high system temperatures.

Since the reduction of system temperatures is of paramount importance for the transformation towards renewable energy sources, studying the effects of night set-backs in buildings' heat demands and radiator temperatures ought to be a priority. Nonetheless, it has received little attention from the district heating research community, probably due to the fact that they are not as commonly applied in Northern Europe.

Research conducted in Italy (Neirotti et al., 2019) and Denmark (Benakopoulos et al., 2022) has shown that a continuous operation of heating systems could bring about a temperature reduction in radiators without a drastic increase in the heat demand of the buildings. Nonetheless, some preliminary calculations presented by this author in Sánchez-García and Persson (2021), showed that, for the building under analysis, heat demand would appreciably rise, probably denying the other benefits.

Based on this background, a further exploration of the impacts of night set-backs in a large array of buildings under various climatic conditions would facilitate the transition towards renewables in Central and Southern European district heating systems.

7.2.2 District heating and cooling potential in Spain

The public debate on energy in the country tends to focus on electricity, to the point that considerations only affecting the electricity system are extended to the entire energy system. Furthermore, little attention is given to heating and cooling, and the little scrutiny on this topic revolves around heat demand reduction through energy refurbishment and rarely touches the supply means.

Beyond the public discourse, there is neither a coherent strategy to decarbonise the heat sector. Prior studies of the energy sector barely addressed the topic (e.g. Aragón-Medina et al. (2018)), and the current *"Plan Nacional Integrado de Energía y Clima"*, National Integrated Energy and Climate Plan, has not built a cohesive strategy for the full decarbonisation of the heating and cooling sector but presents a series of disconnected measures.

In addition, the Comprehensive Assessment on heating and cooling, compelled by the Energy Efficiency Directive, it presents some limitations despite its successes [113]. Firstly, it is based on a bottom-up analysis that ignores the system-wide benefits of district heating and cooling. Second, it does not take into account electricity grid costs for the high deployment level of air-source heat pumps it suggests (57% of the heating and cooling demand). Thirdly, it ignores some promising sources for district heating production such as non-geothermal heat pumps, data centres and hydrogen production. These limitations probably contributed to the low level of district heating penetration suggested by the

[113]Notably, the geographic modelling of the heat demand takes advantage of the highly detailed Spanish Cadastre and has been praised by the Joint Research Centre (Jakubcionis et al., 2018, page 12), although unfortunately this heat atlas cannot be retrieved for further analysis.

study, 10%, which is substantially lower than those suggested by Heat Roadmap Europe 4 (Paardekooper et al., 2018b), sEEnergies (Maya-Drysdale et al., 2022), and paper III of this thesis. Some of the aforementioned criticism is not exclusive to Spain's assessment and Djørup et al. (2019) recommend "*to include cross-sector energy system effects while focusing on the heating sector*", signalling that most countries neglect the benefits of sector coupling.

Departing from these shortcomings, research should address the trade-offs between various shares of district heating, individual solutions and energy conservation measures. In addition, this analysis should be carried out in a holistic framework that takes into account the interactions of the heating and cooling sector with the entire energy system, the benefits of structural energy efficiency and the consequences of the different configurations.

7.3 Non District Heating interests

During the execution of these doctoral studies, I have roughly travelled 41 700 km by rail, crossing Sweden, Germany, the Netherlands, Belgium, France, England, Switzerland and Spain. Sometimes on my own or with my family, and others accompanied by my supervisor and colleagues from Högskolan i Halmstad.

On occasions, time went by while working, contemplating the landscape, or enjoying a conversation. On other occasions, German delays derailed our trip experiences. In any case, these experiences have helped me to reflect on the state of European rail travel and the benefits and drawbacks of the different national approaches to rail.

On the one end, there lies the high-speed separated network approach led by France. *L'Hexagone* has developed over the last decades a radial high-speed network that enables very fast travel [114] through main locations [115], and has probably contributed to its high rail turnover [116]. However, as Worth (2023) has pointed out, the country suffers from poor timetabling and a lack of coordination between long-distance, regional rail, excessive dwelling times, and the substitution of ordinary rail services by low-cost Ouigo services, which are incompatible with ordinary services. On the contrary, Germany's high-speed network is more patchy [117] and hence, travelling speeds tend to by much lower as illustrated by Brons et al. (2023, page 7), and the combination of services with very different speeds (e.g. national vs regional) in the same infrastructure leads to high *padding* rates and operation difficulties as repeatedly criticised by Levy (Levy, 2019a, 2019b, 2019c, 2019d, 2019e, 2021).

[114] As an example, the trip between Hendaye and Strasbourg takes 7,5 hours for covering 1 200 km, this is, it has a mean speed of 160 km/h, despite the egregious crossing of Paris.

[115] I.e. passing by Paris.

[116] An average Frenchman travelled 1 484 km in 2024, just after an average Swiss and average Austrian with 2 354 km and 1 540 km, respectively (European Commission, 2025e, 2025f).

[117] This observation can be drawn from Europe's high speed rail map (Wikimedia, 2025).

However, the country has *clock-face scheduling* [118], good connectivity with all population centres and aims to develop *Deutschlandtakt* (Stoll et al., 2024), a national integrated periodic timetable (Lombardi, 2010; Hauck, 2023). Under this planning paradigm, a strategic timetable is designed to enhance network effects, minimise transfer penalties and provide good connectivity from-everywhere-to-everywhere (Chitti & Beria, 2025).

Following the trail of France, Spain has constructed one of the World's most extensive high-speed rail networks since the inauguration of the first high-speed line between Madrid and Seville in 1992. The main benefit brought about by this new grid is the drastic curtailment of travel times between Madrid and the rest of the country, which has generated a substantial increase in passenger demand [119] and the near termination of air travel in key routes. However, the planning of this network seems to have been infrastructure-driven, similarly to Italy (Chitti & Beria, 2025), rather than following a certain strategic timetable designed to meet the potential demand. In addition, the incumbent national operator, *renfe*, shares many of the issues identified by Worth on France's railway system; it is characterised for its irregular timetables, poor coordination between national, regional and local trains [120] and point-to-point operations *à la* airline [121], among others.

Given the benefits that a national Integrated Periodic Timetable has brought to Switzerland (Finger et al., 2014), the deployment of such a schedule in Spain could improve the geographic connectivity of the system and increase the share of rail in the transport sector. These enhancements would undoubtedly help to tackle carbon emissions from the transport sector. Unfortunately, little attention has been paid to this issue in the research community and to the best knowledge of this author, only three inquiries have addressed this problem (Lombardi, 2010; Andersen, 2018; Luque-Velázquez, 2022). Therefore, it could be of interest to develop a national Integrated Periodic Timetable and an assessment of the improvements it could bring about to the railway system.

[118] Trains departure times follow cycles, this is, every ten minutes, quarter, half-hour, hour, etc.

[119] Demand rose 51% from 476 km/capita to 720 km/capita between 2004 and 2023.

[120] It is exemplary the fact that local trains are not sold through the ordinary means.

[121] For instance, until recently it was not possible to purchase trips between city pairs that involved a connection in its online platform. Furthermore, connections involving more than one connection are not yet shown to the user despite being possible in Deutsche Bahn's or ÖBB's travel planners.

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Chapter 8

Scientific publications

Paper I

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Further investigations on the Effective Width for district heating systems

Luis Sánchez-García*, Helge Averfalk, Urban Persson

School of Business, Innovation and Sustainability, Halmstad University, 301 18 Halmstad, Sweden

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Abstract

District Heating is a cornerstone for the decarbonisation of the heating and cooling sector in Europe. Nonetheless, this technology is currently absent in a majority of the continent's urban areas, and hence the need for appropriate methods by which to estimate the cost, as well as underlying cost parameters, to assess the feasibility of developing district heating networks is of general interest. One key underlying cost parameter, the concept of Effective Width, which is the ratio between a land area and the trench length within that land area, is the focus quantity of this work. Effective Width enables a first order assessment of the total route length of pipes in a given urban area and, together with the average diameter of the pipes, allows an estimation of the investment cost of installing district heating pipes. However, initial implementations of the Effective Width have been based on rather limited empirical evidence, such as a small set of cases and often disregarding service pipes due to lack of data. Another shortcoming of previous studies is the extrapolation of established relations into more sparsely populated areas. By assembly of a richer database, which contains building data, heat consumption data in the supplied areas, as well as actual network information (numerical and geographical), provided by several district heating companies in Denmark and Sweden, the objectives of this study are twofold: first, to improve the general understanding of Effective Width and its relation to building density, and secondly, to study the particular case of sparse areas. The results of this study provide new insight to enhance our understanding of the Effective Width concept which may facilitate better assessments of future district heating systems.

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Keywords: Effective Width; Plot ratio; Distribution capital cost; Heat density; District heating; GIS

* Corresponding author.
E-mail address: luis.sanchez_garcia@hh.se (L. Sánchez-García).

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Peer-review under responsibility of the scientific committee of the 17th International Symposium on District Heating and Cooling, Nottingham Trent University, 17th DHC Symposium, 2021.

1. Introduction

1.1. Overview background

District heating has been recognised as one of the most cost-effective means of decarbonising Europe's heating and cooling supply in urban areas due to its ability to integrate industrial excess heat that would otherwise be wasted and renewables such as solar thermal, geothermal or heat pumps in an economic manner.

Nonetheless, the current heat market penetration average of these networks in the EU is only around 10%, with significant regional variations throughout the continent. Furthermore, a considerable share of the capital cost for a district heating system lies in the pipe network [1]. These two issues lead to the search for a simple but powerful approach to estimate the cost of building new district heating networks in undeveloped areas.

Persson and Werner [1] presented one of these methods for estimating the cost of constructing district heating networks in a series of major European cities. In this study, they took advantage of the concept of Effective Width previously developed by Werner [2]. Later this model has been employed in the Heat Roadmap Europe project series [3], which addressed the major European heat markets and by Fattori et al. [4] and Macchi et al. [5] for a study of Italy.

The basics of Persson and Werner's capital cost model are presented in Eq. (1), where C_d is the specific piping cost (€/GJ[1]), a, is the annuity for the desired interest rate and amortisation period (−), I, the total investment (€) and Q_s the sold heat (GJ). If these two latter parameters are divided by the pipe length, the total investment cost becomes a specific investment cost per metre of pipe, I_u (€/m), and the sold heat turns into the linear heat density, Q_s/L (GJ/m), the quintessential parameter in district heating networks [6]. The unit cost per metre may be expressed by means of a linear function of the average pipe diameter, d_a (m), and the linear heat density, Q_s/L, may be obtained as the product of three parameters, the specific heat demand, q (GJ/$m^2_{\text{floor area}}$), the plot ratio, ε ($m^2_{\text{floor\_area}}/m^2_{\text{land\_area}}$), and the Effective Width, w ($m^2_{\text{land\_area}}/m_{\text{pipe}}$). The product of the specific heat demand and the plot ratio renders the land heat demand density (GJ/$m^2_{\text{land\_area}}$); this is, the amount of heat by unit area of ground.

$$C_d = \frac{a \cdot I}{Q_s} = \frac{a \cdot {}^{I}/_{L}}{{}^{Q_s}/_{L}} = \frac{a \cdot I_u}{{}^{Q_s}/_{L}} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{\frac{Q_s}{A_f} \cdot \frac{A_f}{A_L} \cdot \frac{A_L}{L}} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{q \cdot \varepsilon \cdot w} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{q_L \cdot w} \tag{1}$$

The Effective Width represents the area covered by a metre of pipe, as shown in Eq. (2), and it is the sole parameter in the previous equation that cannot be readily estimated from the built environment.

$$w = {}^{A_L}/_{L} \tag{2}$$

1.2. Aim

Persson and Werner presented in [7] an analysis of several district heating systems in Sweden, from which resulted a series of expressions relating the Effective Width with the plot ratio. More recently, Fattori et al. have taken advantage of the Italian Census and Open Street Maps to estimate the Effective Width for not only distribution but also service pipes in areas with different building densities. Furthermore, they have also introduced a new independent variable, the number of buildings, to correlate with the effective width.

Notwithstanding the progress attained by this previous research, low-density areas remain largely uncharted. This paper aims to address this issue and provide new evidence on Effective Width's behaviour in sparse areas. Furthermore, this investigation will address both distribution and service pipes, which account for most of the network's length and will explore the relationship of Effective Width to two parameters of building density, the plot ratio and the number of buildings per unit of land area.

1.3. Limitations

This research has been built on the empirical data of one extensive district heating system in Denmark. Consequently, although this research represents an improvement regarding previous work, the results here presented will need to be confirmed by further data collection and analysis.

[1] Specific units are indicated for the sake of clarity, but any set of consistent units may be applied.

2. Data

This study has been assembled on the analysis of an existing district heating system and its urban environment. The district heating network data stems from Fjernvarme Fyn, a district heating company owned by the municipalities of Odense and Nordfyn in Denmark with more than 67.000 m, serving more than 200.000 persons [8]. The network consists of approximately 2.264 km of district heating pipes.

The company has provided a Geographical Information System (GIS) of the network containing, among others, the shape of the network, the type of pipe (transmission, distribution, service) as well as the diameters of the pipe (internal and insulation diameters) [9].

Furthermore, an extract from the Danish Building Register [10] has been obtained from Aalborg University [11]. This register indicates, at a building level, the total floor area dedicated to different purposes thereof, only the likely heated types have been considered: residential (field 217), commercial (field 218) and other (field 225).

The building data was linked to a vector point layer elaborated by '*Danmarks Adresser*' [12] with a single feature for each building. This point layer has been, in turn, associated with a polygon layer containing the cadastral parcels (*matrikelkortet*), published by '*Kortforsyning*' [13].

3. Method

The geographic data has been processed in the R language [14] with extensive use of the sf (*simple features*) package [15,16]. Later, the results have been imported into QGIS [17] for easy visualisation and into MATLAB [18] for further analysis.

The first step has consisted of creating a homogeneous grid of one-hectare cells covering the entire extent of the network. For this purpose, it has been employed the same projection as Heat Roadmap Europe, the Lambert Azimuthal Equal Area with EPSG: 3035 [19]. This grid has been later used to calculate the different parameters at each single cell.

As explained above, the Effective Width is the ratio between the ground area and the pipe length within that area. Therefore, its determination requires an evaluation of both the length of the different pipes (distribution and service) and the building density for each cell of the grid.

The process for the pipe length assessment, which has been illustrated in Fig. 1, consists of two steps: initially, it is performed an intersection between the pipe network and the cell to be examined. Secondly, the length of the two types of pipes is summed separately. Importantly, in the second step, it was necessary to consider that, in some cases, the forward and return pipes were drawn separately.

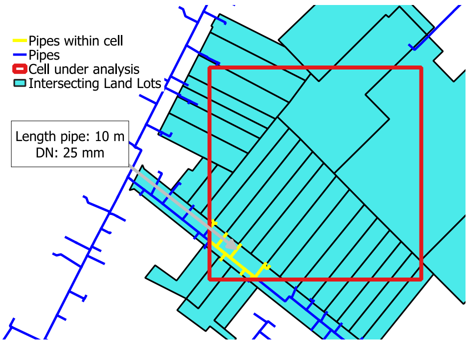

Fig. 1. Determination of pipe length at individual cell.

The determination of the number of buildings and floor area, and hence the plot ratio, presents the difficulty that buildings and land lots are seldom totally within the cell under evaluation. Most often, a land lot stretches over several cells as exemplified in Fig. 2.

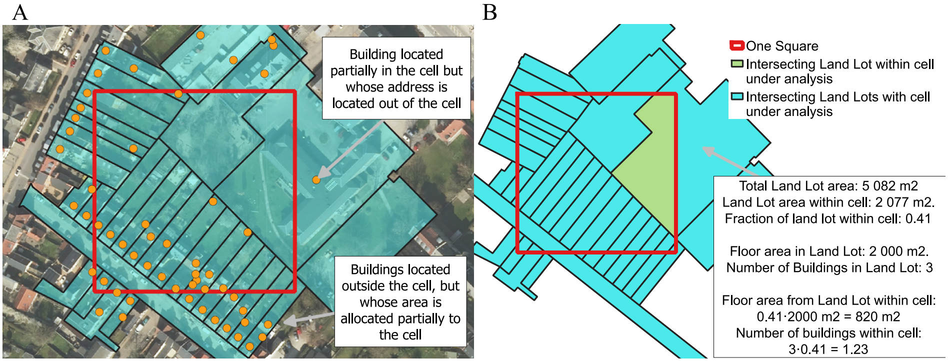

Fig. 2. Determination of plot ratio and number of buildings at individual cell.

The solution to this problem has been to allocate these two characteristics according to the land lot's proportion of ground area within the cell under analysis. This method provides a more even spread of the number of buildings and floor areas over the cells, but it has also resulted in a fractional number of buildings in many of the cells.

3.1. Cell aggregation and analysis

The information contained in the original grid of one-hectare cells has been aggregated into larger *supercells* by grouping adjacent cells. In this clustering, the total pipe length of the different pipes, the floor area, and the number of buildings has been simply summed. This summation has been followed by the recalculation of the derived parameters (plot ratio, number of buildings per ha, Effective Width) for the new *supercell*.

A regression analysis has been carried out into the resulting datasets, one for each *supercell* size. In this examination, the dependent variable, the Effective Width, has been linked to two different independent variables, the number of buildings per ha and the plot ratio. Since both independent variables are highly collinear (in the log–log scale), their concurrent utilisation does not render any improvement to the model, and hence only bivariate analyses have been performed. Moreover, whereas the utilisation of the plot ratio as a predictor has had a long tradition, the employment of the number of buildings is a novel proposal by Fattori et al. [4] and Macchi et al. [5].

The best fits have been obtained for a power regression represented by the generic Equation (3), similar to previous studies by Werner and Persson, where x is the measure of building density utilised. To limit the influence of outliers in the regression, all data points with a Cook's distance higher than four have been removed.

$$w = \kappa \cdot x^{\eta} \qquad (3)$$

4. Results

In the following sections, the results obtained thanks to the analysis of Fjernvarme Fyn's network are shown. The first segment deals with the optimal *supercell* size, whereas the second part focuses on the regression results for the chosen *supercell* size.

4.1. Optimal supercell size

In Fig. 3 it has been depicted the coefficient of determination for different *supercell* sizes. It can be appreciated that this statistic improves rather fast with larger *supercell* sizes, but then it reaches a plateau around a *supercell* size of 10–25 ha, and additional increases do not render much better results.

These outcomes may be explained by the fact that very small *supercells* are not likely to provide a good representation of the urban fabric, and very large *supercell*s are bound to include both urban and non-urban areas,

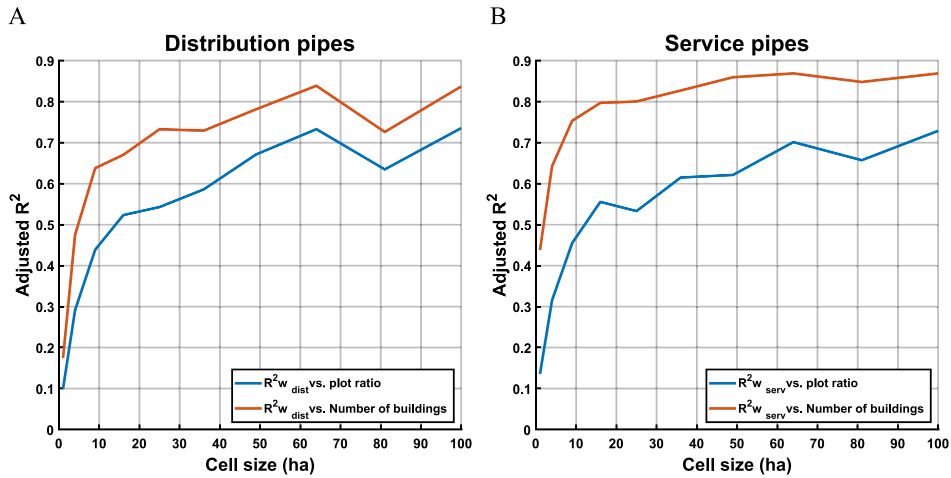

Fig. 3. Coefficient of determination for different *supercell* sizes.

therefore, weakening the relationship between city shape and Effective Width. The former could be clearly seen in Figs. 1 and 2, where the represented cell of one hectare contains a considerable number of buildings but a very short length of district heating pipe.

Regarding the explanatory capacity of the two studied variables, the number of buildings and the plot ratio, the former delivers better results than the latter, although this difference is significantly more prominent in the case of service pipes. This seems a logical outcome since, for example, in two areas with the same plot ratio but different number of buildings, the one with the higher number of buildings is likely to have longer pipes, especially in the case of service pipes, due to the requirement of a service pipe per building.

In Fig. 4 it is shown the two equations parameters, the constant, κ, and the exponent, η, for various *supercell* sizes and pipe types. The exponents are similar for the two explanatory variables, but the constants differ substantially. Besides, the exponents experience the most considerable variations in the smallest *supercell* sizes, but the change is lower above *supercell* sizes 15–30 ha.

Apart from the curve's adjustment to the data, it is necessary to investigate the effect that *supercell* size has on the Effective Width, since choosing a given *supercell* size's parameters could lead to an overestimation of the Effective Width. The simultaneous impact of the exponent, the constant and the plot ratio/number of buildings results in different behaviours depending on the value of the explanatory variable. In low plot ratios (<0.1) or low number of buildings (<10 Buildings/ha), and if the building density remains constant, the effective width increases with larger *supercell* sizes up to a *supercell* size of 15–30 ha, above which the Effective Width remains fairly constant. Therefore, more extensive *supercell* sizes render lower pipe length, and hence, an underestimation of the piping cost. In higher densities, the Effective Width experiences the opposite behaviour, and larger *supercell* sizes result in slightly lower Effective Width and hence, longer pipes.

The occurring performance at low plot ratios probably has the same motive as the one suggested above for the value of the adjusted R^2. Larger *supercell*s are bound to include both urban and non-urban areas, which results in an expansion of the numerator without a concomitant growth of the pipe length. The opposite behaviour in the cases of higher densities does not have such a straightforward explanation, but it may be affected by the lower bound the Effective Width has, an issue which will be later explored in further detail.

In summary, and in the range of low plot ratios, which is the primary purpose of this study, larger *supercells* produce better adjustment between the Effective Width and the explanatory variables but also higher Effective Widths and shorter pipe lengths, which would reduce the investment cost. A balance of these two opposite needs, reasonable adjustment and not underestimating the pipe length, would suggest a compromise *supercell* size in the range of 15–30 ha.

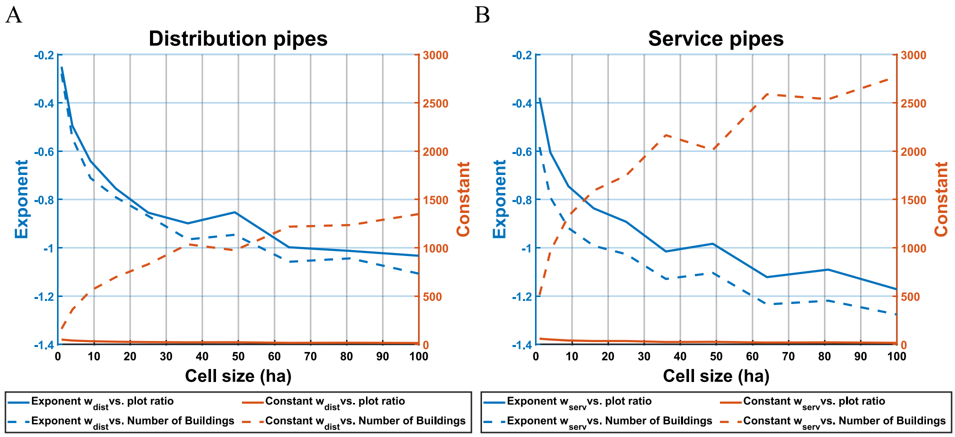

Fig. 4. Model parameters for different supercell sizes.

4.2. Results for optimal supercell size

The subsequent figures show the individual data points and the respective power regressions for a *supercell* size of 16 ha (400 m × 400 m), which is at the lower end of the compromise range. The values of the exponent and the constant have also been presented in Table 1.

Table 1. Parameters for a *supercell* size of 16 ha.

Pipe type	Plot ratio		Number of buildings per ha	
	Exponent	Constant	Exponent	Constant
Distribution	−0.7541	28.20	−0.7903	696.4
Service	−0.8366	35.35	−0.9917	1.592

On the one hand, it can be clearly appreciated in Figs. 5 and 6 that the dispersion around the regression curves is much lower if the number of buildings is used as the explanatory variable, hence the higher coefficient of determination Moreover, residuals are distributed normally, whereas this does not occur with the plot ratio. In this latter case, the distribution of the residuals is slightly skewed, thus raising doubts on the suitability of the model.

On the other hand, there seems to exist a lower bound for the Effective Width, especially in the case of distribution pipes. For this type, the Effective Width seldom falls below 50 m, suggesting that it is rare that a hectare of land requires more than 200 m of pipe. For service pipes, this lower bound seems to be absent when the number of buildings is used as the predictor. However, if the plot ratio is utilised instead, the Effective Width experiments a minimum of 45 m at a plot ratio of 0.15, but higher plot ratios have higher Effective Widths. A reason for this might be the fact that above this threshold, higher plot ratios do not correspond to a higher number of buildings but, on the contrary, to smaller amounts, i.e., in areas with high plot ratios, buildings also tend to be larger.

Based on this assessment, the general Effective Width equation could be reformulated according to Eq. (4), where w_{min} may be around 55 m for distribution pipes, which is consistent with the value provided by Persson et al. [3], and 45 m for service pipes.

$$w = max(\kappa \cdot x^{\eta}, w_{min}) \quad (4)$$

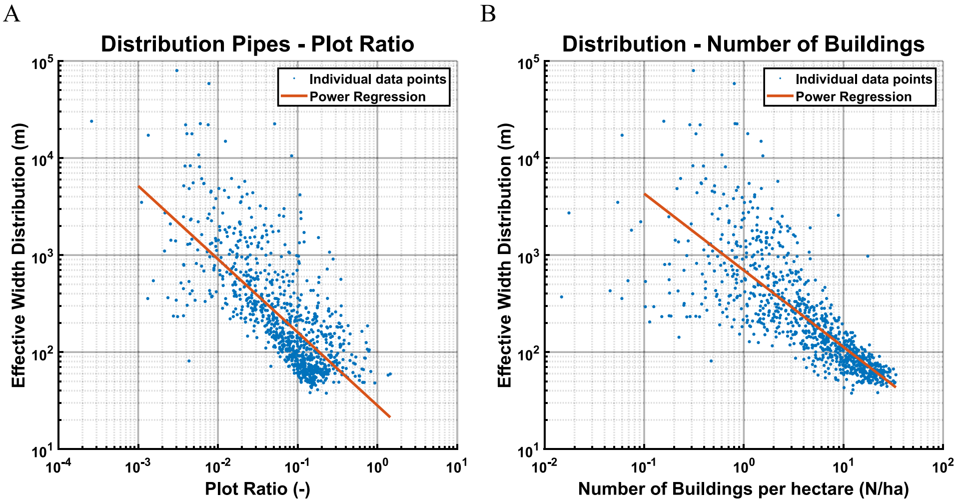

Fig. 5. Effective Width for distribution pipes as function of the plot ratio and the Number of Buildings for a 16-ha *supercell* size.

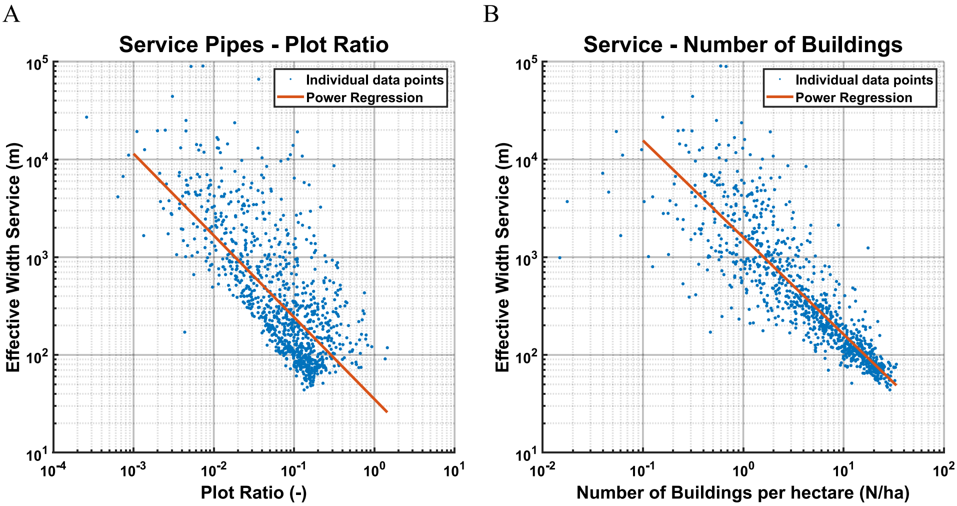

Fig. 6. Effective Width for service pipes as function of the plot ratio and the Number of Buildings for a 16-ha super *supercell* size.

5. Conclusions

The Effective Width concept offers a simple but fast solution for the estimation of the capital cost of District Heating networks in undeveloped areas. This research has provided new expressions for both distribution and service pipes in low-density areas and confirmed the lower bound of Effective Width in high-density areas. Furthermore, it has explored and compared the utilisation of two explanatory variables of building density, drawing the conclusion that the number of buildings represents a more accurate alternative than the plot ratio for estimating the Effective Width.

During the elaboration of this study, information from additional district heating systems in Denmark and Sweden has been received, and its analysis will shed further light on the Effective Width at different ranges of building density.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Paper II

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Understanding effective width for district heating

Luis Sánchez-García *, Helge Averfalk, Erik Möllerström, Urban Persson

School of Business, Innovation and Sustainability, Halmstad University, PO BOX 823, SE 30118, Halmstad, Sweden

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A B S T R A C T

District heating is one of the technologies that can contribute to the decarbonisation of the European heat sector. Nonetheless, these infrastructures only deliver about a tenth of the heat demands in the continent. Therefore, it is essential to assess the expansion potential of these systems and to identify which areas should be target for further investigations, which calls for easy-to-use and straightforward methods such as Persson & Werner's network capital cost model. Pivotal parameters of the model are the effective width, a metric of trench length by land area, alongside the average pipe diameter and the linear heat density. This study has carried out an in-depth analysis of these crucial parameters with respect to both distribution and service pipes in a large Danish district heating network, which has allowed to explore the behaviour of effective width in a broad range of building densities and derive new equations for both effective width and average pipe diameter. The model has subsequently been validated in another large network in Denmark and several minor districts in the same country, showing the accuracy of the model on an aggregated level.

1. Introduction

The bleak consequences of global warming [1], as well as the economic vulnerability unveiled by the various energy crises, demand a drastic reduction of fossil fuel use in the different sectors of the energy system. One of these sectors, comfort heating and cooling, accounts for a third of Europe's final energy demand and is still predominantly supplied by fossil fuels [2], therefore, being a priority target for decarbonisation.

District heating is one of the possible solutions for the decarbonisation of the heat sector in urban areas thanks to its ability to recover heat that would otherwise be wasted or harvest local heat sources more cost-effectively [3]. Over the last decades, this capacity has caught the attention of both researchers [4–6], and policymakers [7] to the possibilities of these infrastructures to tackle the aforementioned challenges.

A key question in the debate about the decarbonisation of the heat sector has been where and to what extent district heating can deliver a more cost-effective solution than individual alternatives, be they at building or dwelling level. In an area of a limited extent, e.g., a city, this issue can be solved with detailed studies that, among others, take into consideration the building characteristics, the street network, the topography, temperature levels and so forth. However, the study of larger areas, such as a region, a country, or the entire European continent, demands simpler methods that deliver approximate but robust first-order solutions that can guide policy makers.

1.1. The capital cost model

One of these approximate approaches is the capital cost model developed by Persson & Werner [8]. This model is presented in Equation (1), where C_d is the specific network cost[1] (€/GJ), a, is the annuity rate (−), I, the total investment (€) and Q_s the delivered heat (GJ). After dividing by L, the pipe length, the numerator turns into I_u, the specific investment per meter of pipe, (€/m), and the denominator leads to Q_s/L, the linear heat density, (GJ/m). I_u is usually a linear function of d_a, the average pipe diameter (m), and Q_s/L may be determined by the product of two factors q_L, the land heat density (GJ/m$^2_{land_area}$), and w the Effective Width, (m$^2_{land_area}$/m$_{trench}$). The land heat density is the amount of heat demand per unit of ground area, A_L, whereas the effective width is the ratio of land area and trench length. Its inverse, the specific trench length, L_u, would indicate the trench length per unit of ground area.

$$C_d = \frac{a \cdot I}{Q_s} = \frac{a \cdot I/L}{Q_s/L} = \frac{a \cdot I_u}{Q_s/L} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{\frac{Q_s}{A_L} \cdot \frac{A_L}{L}} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{q_L \cdot w} \quad (1)$$

Although Persson & Werner's model could, in principle, provide an accurate cost, this would necessitate the average pipe diameter and the effective width to be known with full certainty, which, in turn, would

* Corresponding author.
E-mail address: luis.sanchez_garcia@hh.se (L. Sánchez-García).

[1] Equivalent of the Levelized Cost of Heat (LCOH) when only the network is considered.

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Nomenclature

C_d	Unit network cost; this is, the annualised investment per unit of delivered heat. [€/MWh]
a	Annuity ratio, the quotient between the principal repayment plus interests, and the initial investment. [−]
I	Investment required for installing district heating pipes in a given zone. [€]
Q_s	Heat demand in the given zone. [MWh]
L	Trench length, which, by convention, is also called pipe length. [m]
Q_s/L	Linear heat density, this is, the heat demand per meter of pipe. [GJ/m, MWh/m]
I_u	Specific investment, this is, investment per unit of trench length. [€/m]
d_a	Length-weighted average diameter in the given zone. [mm]
C_1	Intercept of the cost curve. [€/m]
C_2	Slope of the cost curve. [€/m·mm]
A_f	Floor area of the buildings in the area, typically the gross heated floor area. [m^2]
A_L	Ground/land area in the zone under study. [m^2, ha]
ε	Plot ratio, which is the quotient between the floor area, A_f and the ground area, A_L. [−]
q_L	Land heat demand density or simply the heat density; this is, the heat demand, Q_s, per unit area of ground, A_L. [MWh/ha]
w	Effective width, this is, the ratio between the land area, A_L, and the trench length, L. [m]
L_u	Specific pipe length, this is, the pipe length, L, per unit of land area, A_L, the inverse of the effective width. [m/ha]
L_i	Length of a stretch of pipe with the same diameter, D_i. [m]
D_i	Diameter of a stretch of pipe. [mm]
N_i	Number of buildings located within a hectare cell. [−]
x_i	Plot ratio or Number of buildings
G	Gini coefficient of the distribution of plot ratio or number of buildings within a *super-cell*, (group of several 1-ha cells). [−]
y_i^r	Actual value in a curve fitting. [Various units]
y_i^p	Predicted value in a curve fitting. [Various units]
σ_i	Uncertainty of the actual value in a curve fitting. [Various units]
χ^2	Squared sum of residuals, $y_i^r - y_i^p$, scaled by the expected error, σ_i. [−]

call for detailed sizing. Hence the model is mostly applied with simple correlations of these two parameters to building and heat densities. Here not only lies its main strengths, as the model is fast, easy to use, and not data-intense, but also, its intrinsic limitation; the model is a planning tool that renders a first order assessment that cannot replace detailed dimensioning of the pipe network.

1.2. Literature review

The concept of effective width, one of the keys of the capital cost model, was firstly introduced by Werner [9] in a report prepared for the former Swedish district heating association. That report aimed to explore the cost of establishing new district heating networks in sparse areas, in which context, the effective width was to provide a metric of the efficiency of the district heating network extension. Later, Werner et al. continued to develop the concept [10].

In the two reports Werner measured the land area as the "*markarea*", as defined by Ref. [11]. This "*markarea*" was roughly the sum of the land lot plus a certain amount of the street area.

In addition to the initial data gathered by Werner, Netterberg & Isaksson examined 34 districts, "*nyckelområden*", in the Swedish cities of Gothenburg and Halmstad and deduced an expression for the effective width, which they later employed in a feasibility study for the English town of Slough [12]. In this study, the authors decided to use the entire land area of the studied districts rather than the "*markarea*" since Werner wished to investigate whether the entire land area, which is more readily available, could be used to determine the effective width.

The original dataset collected by Werner based on the "*markarea*" concept and the more recent dataset based on "*nyckelområden*" were later published in Ref. [13]. One year later, these authors made the first major application when they analysed the future competitiveness of district heating networks in 83 settlements in Belgium, Germany, France, and the Netherlands [8]. These authors also provided a new relationship between the average pipe diameter and the linear heat density.

Shortly after the previous papers were published, Dalla Rosa provided the effective width of two different projects, in Canada and Denmark, as a result of the pipe sizing carried out. The values for the effective width were relatively low, so both distribution and service pipes were probably included in the calculation [14,15].

Nielsen and Möller developed their own expression for effective width based on 88 district heating areas in the city of Aarhus (Denmark) and applied it to the estimation of the possibilities for district heating expansion in the country [16].

The seminal Heat Roadmap Europe 4 project extended the application of the effective width method to the 14 largest European heat markets. The heat demand model was presented in Ref. [17], accompanied by preliminary results on network costs. These initial outcomes were extended in Ref. [18], where the authors drew the ground-breaking conclusion that an increment of the penetration of district heating in Europe towards 50% of the total heat demand in the studied countries would be technically viable.

Leurent et al. [19] utilised the capital cost model by Persson & Werner and the effective width concept in order to estimate the distribution cost of developing a new district heating network in the city of Lyon. This assessment was later used to compare the economic and environmental feasibility of a district heating system fed by either nuclear waste heat or large-scale heat pumps with two decentralised solutions: joule heating and condensing gas boilers. Later, the first author expanded the study area and conducted an assesment of the district heating potential in the entire France [20].

Björnebo et al. also used this method for estimating the potential of district heating systems in the north-eastern United States [21].

The capital cost model has also been integrated into broader schemes to estimate the costs of both distribution and transmission pipes. One of these methods has been proposed by Ref. [22], which also incorporates the effect of various market shares in the final specific piping cost.

Researchers from *Politecnico di Milano* took a novel approach in Ref. [23], where they related the effective width to another indicator of building density, the number of buildings per unit of area, rather than the former approach of using the plot ratio as the independent variable. These new formulas were utilised in several studies in the city of Milan

[24,25] and the entire Italy [26].

Although indirectly, Chambers et al. also used the effective width concept to estimate linear heat densities of potential district heating areas in Switzerland [27]. These authors related the specific trench length per unit of ground area, i.e., the inverse of effective width, to the specific number of buildings by means of a power function.

The guidelines for implementing low-temperature district heating [28] have provided effective width values for a series of cities throughout Europe. However, no new expression was indicated.

Recently, Fallahnejad et al. constructed a series of synthetic networks with the aid of the mixed integer linear programming (MILP) algorithm *DHmin* and compared the network costs with those delivered by the effective width method [29], showing a generally good agreement between both approaches. Later the same authors applied the concept to a country-wide study in Austria [30].

Other simple methods developed over the years are the one presented by Kristjanson and Bøhm [31] or the one proposed in the Dutch guidelines [32]. In the latter one, it is established that the specific trench length is inversely proportional to the square root of the land area and hence, does not depend on the building environment.

Aside from the utilisation of the method for determining the potential for district heating growth in new areas, other authors have also used the approach with different intentions. This is the case of [33], which applied this procedure in a broader study of the competitiveness of ultra-low temperature district heating.

1.3. Research questions

As presented in the previous chapter, a clear definition of land area has not yet been established in the literature, making it difficult to compare the various expressions provided for effective width. In addition, attention to sparse areas has been scant to this date since studies on effective width, have employed datasets from, among others, Sweden, and Italy, where district heating predominantly supplies medium to high heat density areas. Furthermore, no prior research has charted the behaviour of service pipes' average diameter. Finally, only one prior study has addressed the critical issue of model validation, which raises doubts on the accuracy of the model's results.

This study intends to fill this gap in knowledge thanks to the exploitation of comprehensive district heating information from Denmark, a country, that has developed district heating extensively in both high- and low-heat density areas. Hence, this research intends to address the following research questions:

1. What is the behaviour of effective width when a uniform grid is employed, especially in low-density areas?
2. What is the relationship between the average pipe diameter and the linear heat density for service pipes?
3. How accurate is Persson and Werner's capital cost model in uniform and irregularly shaped areas?

Two main limitations can be drawn on this research. On the one hand, the simplicity of the model can only lead to approximate results and its success may only be judged on the light of this issue. On the other hand, this research has mostly fed on Danish and to a lesser extent on Swedish data. Therefore, its extrapolation to other locations should be executed with caution.

2. Method and input data

This work relies on several large datasets made available by district heating system operators in two large Danish systems and complementary datasets on floor areas and heat demands for these areas. To these authors knowledge only the data pertaining to one network, Aarhus, has been used in prior research [16], and the remaining data has not been utilised before.

2.1. Network data

The first system is Fjernvarme Fyn, a district heating company serving more than 200 000 persons [37,86]. The network consists of approximately 2259 km of district heating pipes; thereof 838 km, 1215 km, and 205 km are service, distribution, and transmission pipes, respectively.

The second system is AffaldVarme Aarhus, a municipality-owned district heating company, which directly supplies most of the city but also delivers heat to several consumer-owned companies [34,35]. As of 2020, the company supplied heat to over 330 000 persons [36] with a network consisting of approximately 2422 km of district heating pipes; thereof 932 km, 1221 km, and 269 km are service, distribution and transmission pipes, respectively.

Both companies have provided a Geographical Information System (GIS) with shape format of the networks containing the outline of the network, the type of pipe (transmission, distribution, service), as well as the pipe diameters [37,38].

2.2. Heat demand and floor areas data

The Danish IT and Development Agency has provided the heat demand of all district heating consumers from the municipalities served by the two companies [39]. In total, 2 404 787 measurements were received. The data was provided in a tabular format with information e. g., on consumer addresses, start and end dates of billing periods, the amount of energy used alongside its unit and supply company identifiers. Data as early as 2001 was available, but 98.8% of the data were recorded after 2009.

The heat demand was generally provided in energy units, but in 28% of the entries (mainly from the municipality of Odense), the heat demand was indicated as circulated volumes (m^3), which were converted into heat demands utilising an average cooling of 35 °C for all the measurements [40,41].

Regarding temporal variation and climate correction, the average heat demand was calculated as the annualised ratio between the total heat demand and the billed period following Grundahl & Nielsen [42]. Consistent climate correction of the heat demand was not considered feasible, since consumption data was often provided at a unit[2] or building level, with, in some cases, overlapping billing periods.

Addresses' information was retrieved with the aid of the public API (Application Programming Interface) *DAR Historik* [43]. This information was crossed with the heat meter's address to enable the geolocation of each consumption.

Finally, in the case of the heat demand from the municipality of Aarhus, only the heat demand directly supplied by AffaldVarme Aarhus[3] has been taken into account since it has only been possible to obtain pipe data from this company.

Building information, including floor areas, construction year, status (e.g. standing or demolished) and building type (e.g., detached, semi-detached, multifamily building etc.) for all buildings in the study areas, has been retrieved from the Danish platform *Datafordeler* [45] through the various API available to that effect.

The starting point was the addresses from which heat demand data was available, from which all the buildings located in the corresponding property were retrieved [46,47]. This data set was subjected to a cleaning process consistent of the following steps. First, all entries with no coordinate data were removed. Second, all entries with no floor area were discarded. In third place, it was rejected all the building types not considered in *Varmeplan Danmark* [48], which are very likely

[2] A building (*bygning*) may be divided in several smaller units (e.g., a flat in a multi-family building, or a commercial premise), which constitute the smallest division of the Danish Cadastre (BBR).

[3] The company was renamed in April 2022 to Kredsløb [44].

non-heated. Given the definition of floor area in BBR, the attained floor areas may be deemed gross heated floor areas as defined by Ref. [49]. Finally, only the buildings connected to heat demands supplied by Affaldvarme Aarhus or Fjernvarme Fyn were further analysed.

2.3. Determination of model parameters at different cell sizes

The first step of the determination of the various model parameters has consisted of the division of the areas supplied by Fjernvarme Fyn and Affaldvarme Aarhus in a uniform grid of 1-ha squared cells. In the second step, based on the information presented in the previous two sections, it has been determined the dependent variable trench length and the two independent variables, plot ratio and number of buildings for each 1-ha cell of the following the same technique presented by Ref. [50]. The trench length is simply determined as the length of the pipe stretches located within the 1-ha cells, whereas for the two independent parameters a slightly more elaborated procedure is applied. Since many buildings extend over more than one 1-ha cell, a building, and its concomitant floor area, is allocated to all the cells intersected by its land lot, proportionally to the land lot area within each 1-ha cell. Later the three parameters were aggregated in squared 16-ha *super cells*.

The average pipe diameter at each cell, d_a, which was not determined in the previous study [50], has been calculated as the length-weighted mean diameter according to Equation (2), where L_i, is the trench length of each trench stretch and D_i, is the diameter of that pipe stretch. As in previous research, the reference diameter has been the *Diamètre Nominal* (DN).

$$d_a = \frac{\sum_{i=1}^{n} L_i \cdot D_i}{\sum_{i=1}^{n} L_i} \tag{2}$$

The dimensionless Gini coefficient, G, has also been determined to measure the inequality of the internal distribution of buildings in the 16-ha-*super cells* by applying Equation (3) according to Ref. [51]. In this equation, n, represents the number of 1-ha cells within a *super cell*, and x stands for the parameter, either plot ratio or number of buildings per ha, whose inequality is measured. The Gini coefficient may vary between zero, which represents perfect equality, and one, perfect inequality. In the first situation, all the 1-ha cells within a super-cell would have the same plot ratios or number of buildings, whereas in the second situation, all the buildings would be concentrated in one 1-ha cell, leaving the other cells utterly empty.

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n \sum_{j=1}^{n} x_j} \tag{3}$$

2.4. Determination of empirical models

The dataset obtained from the analysis of the district heating network of Fyn has been used to determine the relationship between effective width and both indicators of building density as well as new relationships between linear heat density and average pipe diameter for both distribution and service pipes.

These relationships have been established by means of the least-squares method [52–54] as shown in Equation (4), where y_i^r is the actual value, y_i^p, is the predicted value and σ_i is the actual value's measurement error. The regression analysis has been performed in Python with the aid of the *iminuit* interface [55] for the *Minuit* library developed at CERN [56]. Errors in the fit parameters have been calculated after HESSE and MINOS.

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{y_i^r - y_i^p}{\sigma_i} \right)^2 \tag{4}$$

In this study, it is not known the errors, σ_i, in the various measurements (pipe length, pipe diameter or floor area). Hence, it is not possible to apply the χ^2 method directly. Nonetheless, equal uncertainty of all the measurements may be assumed and, in turn, it may be calculated as the standard deviation of the residuals after the fit parameters have been found [54]. This assumption comes at the expense of the goodness-of-fit probability but with the benefit of obtaining the uncertainties in the fit parameters.

In this study, the trench length per unit of area has been employed as the dependent variable rather than the effective width (its inverse). Even though it is unknown, it is reasonable that there exists a certain error in the pipe length measurement, and it can be further assumed that this error may be equal for all the measurements. Consequently, this equal pipe length error would produce effective width errors inversely proportional to the pipe length, i. e., cells with short lengths (and hence high effective widths) would have much higher uncertainties than cells with longer lengths and would be weighed less in the χ^2 method. Previous research has implicitly assumed equal effective width errors, leading to overweighing cells with very short pipe lengths.

2.5. Performance of models

The performance of models has been determined by the following measures: Mean Average Error, *MAE* , the Median Average Deviation, *MAD* [57,58], the Coefficient of Variation of the Root Mean Squared Error, *CVRMSE* [57–59], the Median Symmetric Accuracy, ζ [60], and the Symmetric Signed Percentage Bias, *SSPB*,which are defined in Equations (5)–(9).

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |y_i^r - y_i^p| \tag{5}$$

$$MAD = median(|y_i^r - y_i^p|) \tag{6}$$

$$CVRMSE = 100\% \cdot \frac{1}{\overline{y^r}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i^r - y_i^p)^2} \tag{7}$$

$$\zeta = 100\% \cdot \left(e^{median\left(\left| ln\left(\frac{y_i^p}{y_i^r} \right) \right| \right)} - 1 \right) \tag{8}$$

$$SSPB = 100\% \cdot sgn\left(median\left(\left| ln\left(\frac{y_i^p}{y_i^r} \right) \right| \right) \right) \cdot \left(e^{\left| median\left(\left| ln\left(\frac{y_i^p}{y_i^r} \right) \right| \right) \right|} - 1 \right) \tag{9}$$

On the one hand, as it will be unveiled in the results section, the errors are riddled with outliers. Hence, it has been deemed appropriate to provide a more robust metric, such as the median error along the mean. On the other hand, the determination of the relative errors (MAPE and MAPD) presents the problem of being undefined whenever the actual value is nil. This issue is, rather frequent and forced the elision of those cells to determine the aforementioned metrics. Moreover, MAPE is asymmetric with regard to over- and under-forecasting [61]. This poor behaviour has led to using the Median Symmetric Accuracy instead, which aims to alleviate the problems of MAPE whilst maintaining its interpretability [60].

Regarding the measurement of the bias, the Symmetric Signed Percentage Bias has been employed as it is not affected by the asymmetric distribution of the percentage errors, similarly to the Median Symmetric Accuracy, and provides a "*robust estimate of the central tendency of the error*" [61].

The previous metrics are applied on a cell-by-cell basis, but they do not provide any information on the similarity between the marginal cost and investment curves shown in Fig. 10. In order to assess these curves, the metric *Area error* is defined in Equation (10), where the functions

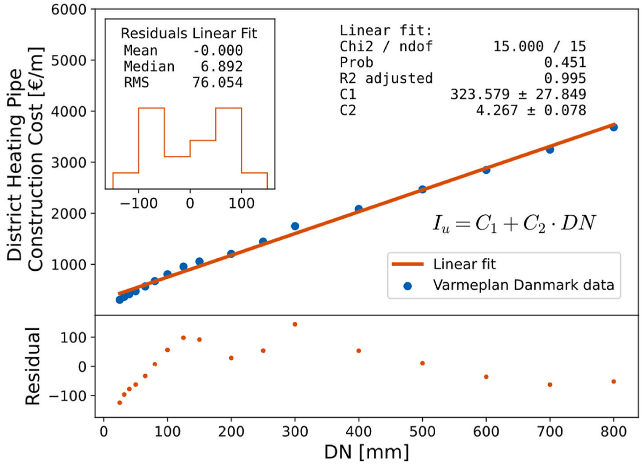

Fig. 1. Specific construction costs for district heating pipes as function of the DN,[61] according to *Varmeplan Danmark*.

Table 1
Summary of characteristics in new district heating supply areas.

Location	Heat Demand (MWh)	Specific Investment (€/MWh)	Heat Density (MWh/ha)	Plot Ratio (−)	Pipe Length Dist. (m)	LHD Dist. (MWh/m)	$D_{a\text{-dist}}$ (mm)	$D_{a\text{-serv}}$ (mm)	C_1 (€/m)	C_2 (€/m·mm)	Ref.
Glostrup	51 173	632	129	0.143	36 730	1.393	42		347 ± 15	4.7 ± 0.2	[70]
Gladsaxe	69 870	497	252	0.188	34 139	2.047	61	25	308 ± 14	4.6 ± 0.1	[71]
Lundtofte	12 815	226	330	0.337	3370	3.803	103	27	333 ± 14	4.5 ± 0.2	[72]
Næstved	49 815	367	110	0.122	36 051	1.382	60		266 ± 12	3.2 ± 0.1	[73]
Tårnby	72 652	368	262	0.297	30 428	2.388	79	40	203 ± 22	4.3 ± 0.2	[74]
Rødovre	47 278	472	289	0.214	21 775	2.171	38	20	301 ± 13	4.6 ± 0.1	[75]
Ballerup	151 546	718	177	0.155	111 070	1.364	42	25	353 ± 13	4.3 ± 0.2	[76]
Herlev	81 671	682	200	0.175	57 661	1.416	48	25	326 ± 15	4.9 ± 0.2	[76]
Gladsaxe N.	89 889	621	186	0.163	56 599	1.588	55	25	250 ± 28	6.0 ± 0.1	[76]
Furesø	81 883	735	121	0.106	68 124	1.202	50	25	295 ± 25	5.4 ± 0.2	[76]
Lyngby	216 412	579	195	0.171	127 433	1.698	55	25	295 ± 25	5.4 ± 0.2	[76]
Frederikssund	78 297	804	112	0.098	68 293	1.146	77	25	250 ± 28	6.0 ± 0.1	[76]
Køge Nyland	33 307	478	148	0.125	27 884	1.194	60	25	259 ± 17	4.1 ± 0.1	[77]
Køge Midtby	39 843	383	210	0.150	20 376	1.955	42	20	259 ± 17	4.1 ± 0.1	[78]

$f_p(Q_c)$ and $f_a(Q_c)$ respectively represent the predicted and actual marginal cost or cumulative investment for supplying a cumulative heat demand Q_c out of a total heat demand, Q_t.

$$Area\ error = \int_{0.05Q_t}^{0.95Q_t} \left(\left| f_p(Q_c) - f_a(Q_c) \right| \right) dQ_c \tag{10}$$

2.6. Pipe costs

The installation costs of district heating pipes for various diameters have been retrieved from the 2021 *Varmeplan Danmark* (Heat Plan Denmark) elaborated by *Aalborg Universitet* [48] and converted to Euro[4] [5] (See Fig. 1).

2.7. New supply areas in Denmark

In addition to validating the model in a homogenous grid, this research has also aimed to test Persson and Werner's capital cost model in irregular areas. This goal has been fulfilled thanks to the information contained in 14 recent Danish socioeconomic analyses, which investigated the conversion to district heating of different areas supplied by natural gas.

Denmark has a long tradition of energy planning at the municipal level [66–69]. In the planning process, it is necessary to execute a cost-benefit analysis of the different heat supply alternatives, which is released during the hearing process.

In every report, it was retrieved the trench length for the different pipe diameters, the installation cost of the various pipe diameters, the heat demand, as well as the total floor area. Furthermore, the ground area was measured in the blueprints to the best extent possible. Based on these values, the derived parameters specific investment, heat density, linear heat density and plot ratio have been determined.

The different neighbourhoods are predominantly suburban and located in the Greater Copenhagen metropolitan region. The heat

[4] Exchange rate of 7.45 DKK/€, conformed to the Danish Central Bank [62] and the Technology Catalogues [63].

[5] This and the following graphs have reutilized code developed by Troels C. Petersen [64].

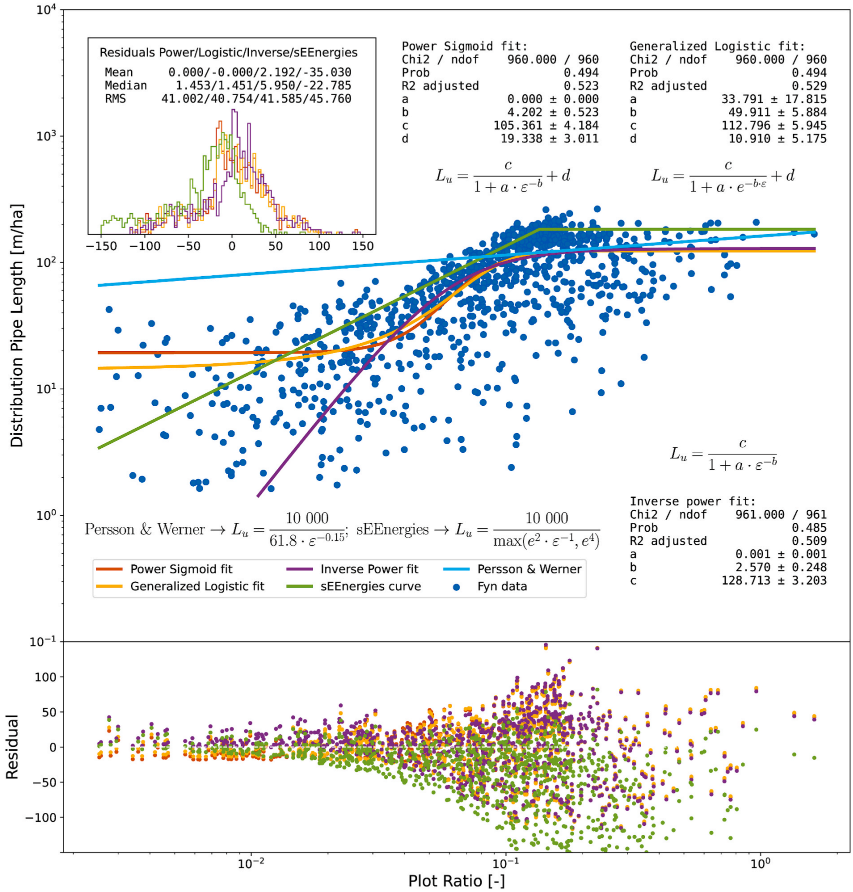

Fig. 2. Distribution pipe length as a function of the plot ratio in the district heating system of Fyn.

demands range from 12.8 GWh/annum to 216.4 GWh/a, the heat densities from 110 MWh/ha to 330 MWh/ha and the specific investments from 226 €/MWh to 884 €/MWh[7], as can be observed in Table 1.

2.8. Determination of confidence intervals

Confidence intervals have been calculated for the 14 districts presented in section 2.7. In these areas, they have been estimated by carrying out one million simulations for each district [79] rather than by applying the usual formulation based on derivatives [53] since the equations are highly non-linear, which would likely render the assumption of normality non-valid. Furthermore, and for simplicity, the symmetric uncertainties have been employed even though the left and the right uncertainties after MINOS differ substantially in some cases.

3. Results and discussion

This section is divided into three parts. First, attention is drawn to the relationship between effective width and various independent parameters. Afterwards, the focus turns to the relationship between linear heat density and the average pipe diameter. Finally, the new expressions are applied in two test areas to verify their accuracy.

3.1. The behaviour of effective width

This section analyses the behaviour of effective width as a function of three independent variables, ε, the plot ratio; N, the number of buildings, which have followed prior research in this area; and G, the Gini coefficient, which has been inspired by the discussions put forward by

[6] DN stands for *Diamètre Nominal*, nominal size according to Ref. [65].

[7] These specific investments would render LCOH ranging from 11.5 €/MWh to 41 €/MWh assuming a 30-year amortization period and 3% interest rate.

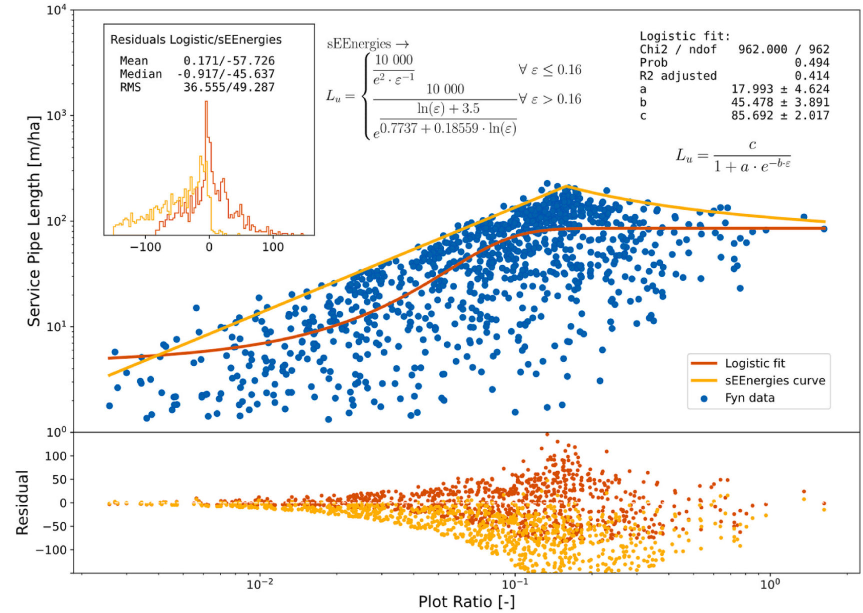

Fig. 3. Service pipe length as a function of the plot ratio in the district heating system of Fyn.

Refs. [13,16] and has been combined with the former two.

The choice for these specific parameters has been realised after careful assessment of a larger array of predictors and formulae. Among others, it was assessed the building densities in concentric annuli around the areas under study, or various distribution functions for the residuals. Furthermore, the employment of neural networks was pondered after a suggestion by Ref. [80], but this option was eventually discarded, since the resulting model would not be as transparent as the formulae presented in the following sections.

3.1.1. *Effective width and plot ratio*

The effective width has previously been related by means of a power function with the plot ratio. However, in prior research [50], it was indicated that this relationship may not be applicable over the entire range of possible plot ratio values. This problem can be clearly appreciated in Fig. 4, where there seems to be a power relationship in the sparsest areas but an upper bound of approximately 200 m/ha (w = 50 m) in high-density areas. Moreover, unlike in previous research, the specific pipe length also seems to present a lower bound in low-density areas; in Fig. 2, the specific pipe length does not fall further than 1–40 m/ha.

The differentiated behaviour of effective width is highlighted when comparing the curve initially proposed by Persson & Werner [8] with the Fyn data. The curve is rather accurate in the densest areas but overestimates the necessary pipe length in the sparsest areas. There are two likely explanations for this drawback; first, the Persson & Werner's data did not include very sparse areas, as these are seldom served by district heating in Sweden; second, the functional relationship used, a power function, fails to capture this differentiated behaviour.

Several expressions have been tested in order to address the preceding shortcomings. The first expression was the "*inverse power fit*", similar to Persson & Werner's expression, but with the benefit of having a horizontal asymptote, which can account for the aforementioned upper bound. However, this equation presents two significant drawbacks. On the one hand, the specific pipe length tends to be underestimated at the lower end of the plot ratio. On the other hand, one of the coefficients is not well defined since its uncertainty is in the same order of magnitude as the value ($a = 8 \cdot 10^{-4} \pm 5 \cdot 10^{-4}$). The second equation to be studied is the so-called "*power sigmoid fit*", which solves the first of the previous equation's issues but is unsuccessful in addressing the second ($a = 1.6 \cdot 10^{-5} \pm 1.7 \cdot 10^{-5}$). The third expression, a generalised logistic function, has tackled all the problems while delivering the highest adjusted R^2. In any case, the three expressions lead to the same values in the densest areas, which are also similar to the values forecasted by Persson & Werner [8].

Finally, together with the various regressions, it has been plotted the equations used in the sEEnergies project [81,82], here referred to as the "sEEnergies curves", which were designed to deliver a conservative estimate of the pipe length. In the main graphs and the residuals histograms it can be seen how these equations nearly always provide an upper bound of the pipe length. The slight discrepancy arises from the fact that the sEEnergies expressions were tailored with a 25-ha *super cell* rather than a 16-ha.

The analysis of the service pipes, depicted in Fig. 3, was directly carried out with a generalised logistic function although, in this case, the lower horizontal asymptote has been omitted since its inclusion did not improve the adjusted-R^2. In a similar fashion, the expressions employed in the sEEnergies project have also been added to the graph. These equations are more successful than their counterparts for distribution pipes in delivering an upper bound of the pipe length, suggesting that the service pipes length is not so sensitive to the cell size.

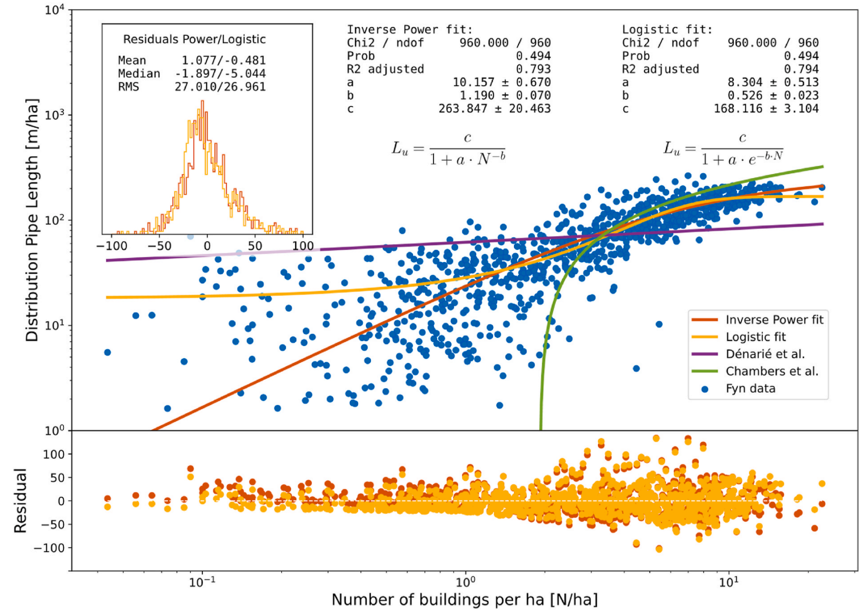

Fig. 4. Distribution pipe length as a function of the number of buildings in the district heating system of Fyn.

3.1.2. Effective width and number of buildings

This section addresses the number of buildings as an independent parameter. As may be appreciated in Figs. 4 and 5, the dispersion of data points is remarkably lower than in the previous two graphs leading to adjusted R^2-values, which lie around 0.8 versus the lower range of 0.4–0.5 in the case of plot ratio.

Another substantial difference with respect to the expressions using the plot ratio is that there does not seem to be a clear difference between the inverse power fit and the logistic fit. Both present similar coefficients of determination, and all the parameters have reasonable uncertainties. The expressions only diverge in the very sparse areas, where the logistic functions lead to higher specific lengths and are slightly more conservative.

In addition, these expressions are compared to other equations proposed by Dénarié et al. [23], Fattori et al. [83]and Chambers et al. [27]. Regarding the distribution pipes, Chambers' curve[8] provides similar trench lengths at high building densities, albeit slightly higher, but leads to substantially lower trench lengths in the lower end of building densities. This might be explained by the lack of sparse Swiss neighbourhoods in the training dataset and the functional choice, a logarithmic curve. On the contrary, Dénarié's curve delivers lower trench lengths in high density areas, characteristic of the Italian urban fabric, with which the equation was tailored. This could indicate that Italian urban patterns are more "*trench-effective*" than Scandinavian patterns, although the difference could also stem from a slightly different categorization of distribution and service pipes, as Fattori's expression, which was elaborated within the same research, leads to higher service trench length. Concerning this latter expression, the predicted service trench lengths are somewhat higher than the existing in Fyn, but the slope of the curves are rather similar.

3.1.3. Effective width and gini coefficient

The relationship between effective width and the Gini coefficient is approximately linear, which has led to testing the expression presented in Equation (11). In this equation, α, indicates the building density parameter, either ε, the plot ratio, or N, the number of buildings; G would be the Gini coefficient, and the italic letters a, b, c, d and g are the equation's coefficients.

$$L_u = \frac{c}{1 + a \cdot e^{-b \cdot \alpha}} + d + g \cdot G \tag{11}$$

The different coefficients have been gathered in Table 2, where the parameter g is always negative. This would entail that areas where buildings are more unevenly distributed, i.e. more packed, present lower pipe lengths, confirming the hypothesis proposed by Persson & Werner [13]. Furthermore, if the coefficients of determination from Table 2 are compared with those of foregoing specifications, it can be appreciated how the addition of the Gini coefficient does increase somewhat the values when the plot ratio is used, but the effect is negligible for the number of buildings.

3.2. Relationship between pipe diameter and linear heat density

In Figs. 6 and 7 it has been plotted the average pipe diameter for both distribution and service pipes as a function of the respective linear heat densities. In the first graph, it has also been added the original data and fit presented by Persson & Werner [8] for the sake of comparison.

In Fig. 6 it can be observed a contrast between the data stemming from Fyn and Persson & Werner's data. Whilst the later clearly point

[8] Although not explicitly stated in the paper, the curve provided by Chambers et al. relates solely to distribution pipes and does not include service pipes [84].

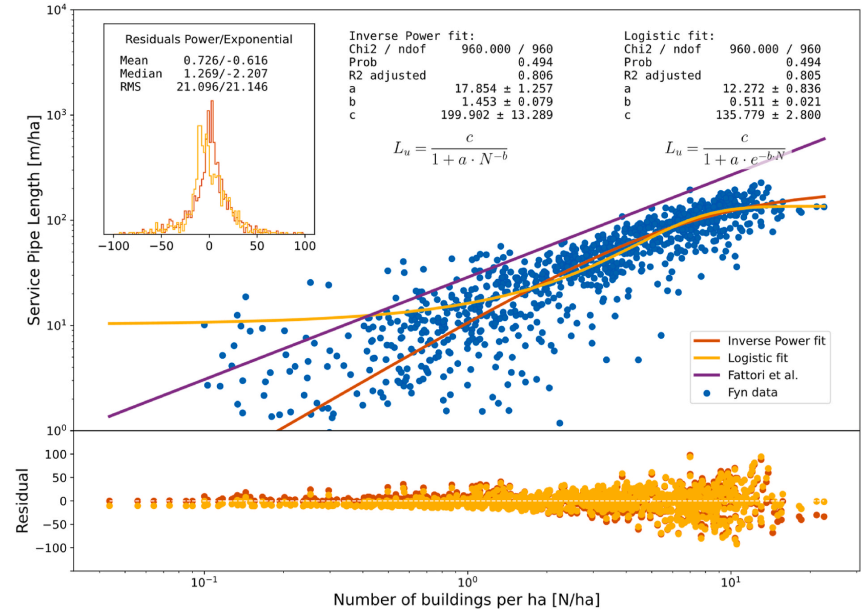

Fig. 5. Service pipe length as a function of the number of buildings in the district heating system of Fyn.

Table 2
Coefficients of regressions with Gini Coefficient.

Regression	a	b	c	d	g	Adjusted-R^2
ε & G – Dist.	46 ± 42	56 ± 11	57 ± 6	98 ± 8	−124 ± 9	0.606
ε & G – Serv.	42 ± 70	68 ± 26	25 ± 5	94 ± 7	−129 ± 8	0.541
N & G – Dist.	2.5 ± 0.9	0.34 ± 0.05	213 ± 30	−25 ± 26	−40 ± 6	0.806
N & G – Serv.	3.9 ± 1	0.34 ± 0.04	163 ± 15	−11 ± 12	−30 ± 5	0.818

towards a logarithmic relationship between the variables; Fyn's relationship is rather more tenuous. It is unclear the underlying reason for this discrepancy. It may be possible that this type of logarithmic relation exists when analysing entire systems, but it vanishes if a sole system is examined in more detail. On the contrary, the difference may merely stem from the different sizes of the datasets and, were more systems to be included in Persson & Werner's dataset, a similar dispersion might be observed.

Notwithstanding the apparently weak logarithmic relationship, the correlation is statistically significant ($z_a = 10.6\sigma$) and thus, a logarithmic equation has been applied to the data, reaching the parameters shown in Fig. 6 (Fyn fit). These coefficients also indicate a slight change with respect to Persson & Werner's fit since the slope of the curve is substantially lower. Analogous behaviour can be observed if a similar equation were to be obtained with the data from section 2.8, suggesting that Danish and Swedish networks may behave differently. However, temperature differences [85] and capacity factors [3] are somewhat higher in Sweden, which would indicate, *caeteris paribus*, the need for lower diameters in this country compared to Denmark. This apparent inconsistency would urge caution when using these empirical relationships.

The data concerning the service pipes, which has been plotted in Fig. 7, unveils a different relationship between the linear heat density and the average pipe diameter. In this case, the diameter remains constant around 16–20 mm up to a value of 7 GJ/m, above which there is a great deal of variation, and the diameter can range from the same low values up to 100 mm. This behaviour could be explained by the fact that low linear heat density areas are predominantly residential with single-family houses with similar sizes, whilst in denser areas, there is a broader range of building typologies and sizes.

Similarly to the distribution pipes, a logarithmic function has been studied. However, it fails to adequately explain the differentiated behaviour of the pipe diameter in different areas and underestimates it in sparse areas, which would require a minimum value of 16 or 20 mm to be included. With the aim of solving these problems, an exponential function has also been studied since it is nearly constant at low values and grows substantially after a certain point. Not only fulfils this exponential fit the last criterion but it also attains a higher coefficient of determination, albeit at the expense of a higher bias.

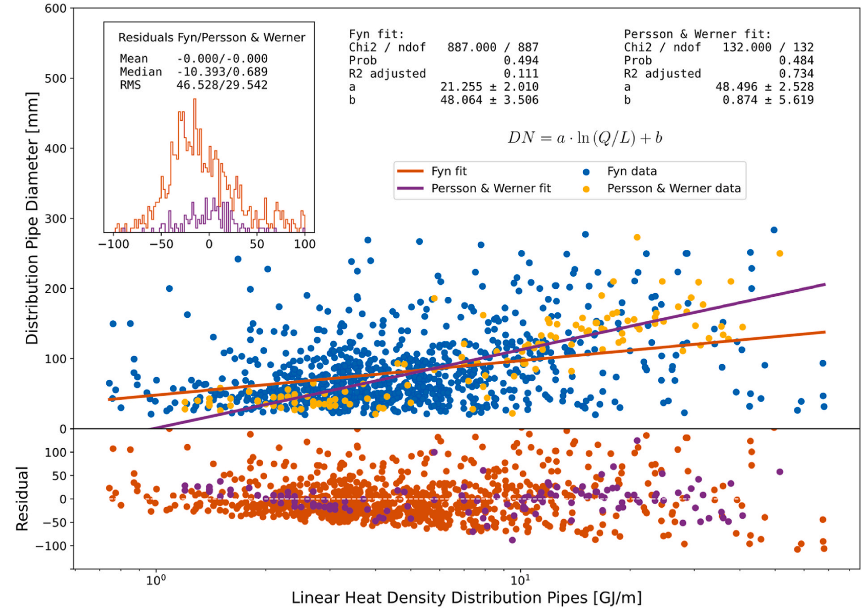

Fig. 6. Average diameter of distribution pipes as a function of the Linear Heat Density of distribution pipes.

3.3. *Accuracy of the capital cost model*

This section is divided into three parts. The first studies the impact of the cell size on the shape of the actual cost curves before any cost model is applied. The second part focuses on the application of the model in a homogenous 16-ha grid in the municipality of Aarhus. The third part analyses the validity of the model in irregularly shaped districts.

3.3.1. *Effect of cell size on the actual network cost*

Before studying the accuracy of Persson and Werner's model, it is essential to assess the effect of cell size in the cumulative cost curves that are usually employed for showing the cost of district heating at different penetration rates.

For that purpose, in Fig. 8 it has been plotted the marginal and cumulative investment for different penetration rates in the city of Aarhus. A common feature of all the curves is that they end in the same value. If all the city area is considered, the influence of cell size vanishes, and the maximum investment (and marginal specific investment) will be the result of taking all the network under consideration. However, when only a part of the city is considered, the cell size does have an impact.

The 1-ha curves present the paradox that it is possible to supply a certain heat demand at nil cost. This can be explained by the fact that if a small cell size is taken, many cells have a certain heat demand but lack pipe network. This issue has a lesser influence when the cell size is larger since a cell with heat demand is more likely to contain a certain amount of pipe length. Hence, the 16-ha curves start growing much earlier than the 1-ha curves, although slowly. This low initial growth stems from merely six 16-ha cells, characterised by the presence of large consumers, which have a heat demand of 438 GWh but only a pipe length of barely 27 m/ha, leading to an investment of just 2.65 million Euros.

The fact that the 16-ha curves are consistently higher than their 1-ha counterparts is likely explained by the same reason. A certain heat demand will be more likely accompanied by the necessary pipe to supply it, the larger the cell is.

These problems with the 1-ha cells would indicate that the curves obtained with them are not likely to provide an accurate picture of the cost of delivering district heating at different penetration levels, since network costs are initially underestimated.

3.3.2. *Validation of the model in the city of aarhus*

This section compares the actual with the predicted network cost on a cell and city basis. The actual cost has been based on the observed trench length, real average pipe diameter and actual heat density, whilst the predicted cost has been estimated with the Equations presented in sections 3.1 and 3.2.

Albeit the various Equations were obtained by applying a *super cell* size of 16 ha, they have been tested in both 1-ha and 16-ha cells.

Firstly, in Fig. 9, it has been depicted the actual network costs as a function of the predicted costs, which have been calculated by applying the logistic and sEEnergies curves for the pipe length. Moreover, the average pipe diameter has been determined by Fyn's logarithmic equations.

Two common trends may be observed in all the graphs. Firstly, the differences between the actual and the predicted costs at individual cells are substantial for both cell sizes showing the clear limitations of the model in small areas. Secondly, the distribution of errors is not independent of the network cost value. This is, in the cheaper areas, the costs tend to be overpredicted, whereas the opposite occurs in the most expensive cells. Additionally, the expenses from the sEEnergies equations are generally very conservative, since predicted costs are persistently higher than actual costs.

There exist some differences between the two cell sizes. On the one

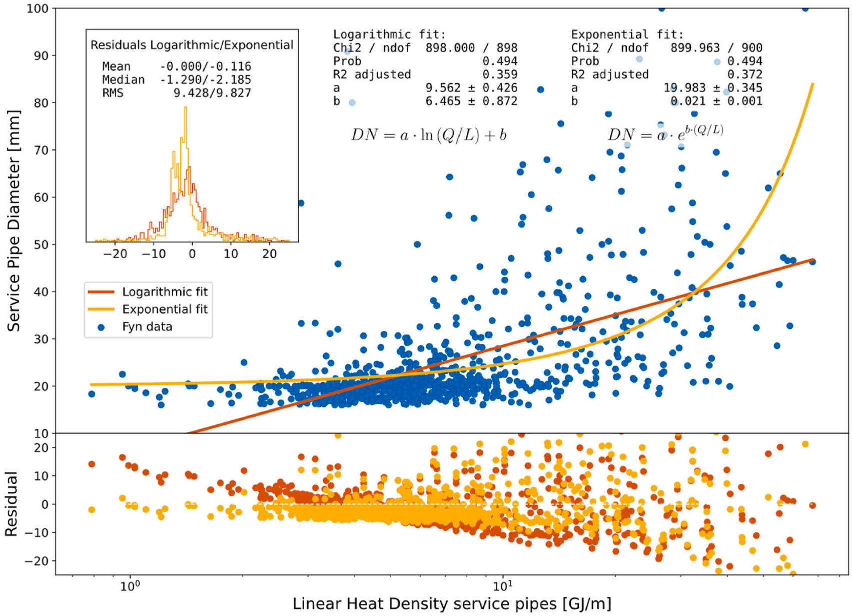

Fig. 7. Average diameter of service pipes as a function of the Linear Heat Density of service pipes.

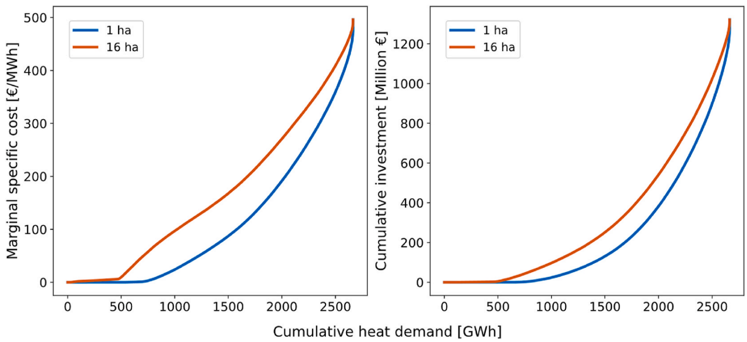

Fig. 8. Effect of cell size on marginal and cumulative investment.

hand, the 16-ha grid leads to less extreme costs than the 1-ha grid, which likely occurs because the larger cell size evens out the heat demand and the trench length. Hence, there are fewer cells with a high heat demand and low trench length or vice versa the larger the cell size is. On the other hand, the sEEnergies equations deliver as expected generally conservative results in the 16-ha cells (with some differences among pipe types), but less so at the higher resolution, 1 ha.

Fig. 9 shows the model's accuracy on a cell-by-cell basis, but this is seldom the sought result in large-scale analysis at a city or regional level. The main goal often is to obtain the marginal cost and investment at different penetration rates; an example of which has been plotted in Fig. 10, where it can be compared these curves for both the actual and predicted costs (logistic regression for trench length). This figure shows how the predicted investment and the marginal cost follow the actual values very closely at a resolution of 16 ha. In contrast, the performance is significantly worse at 1 ha. This high similarity suggests that, despite the inaccuracy of the model on a disaggregated level, the errors cancel each other out when the information is aggregated, leading to surprisingly good results.

Since Figs. 9 and 10 have only presented a graphical overview and a

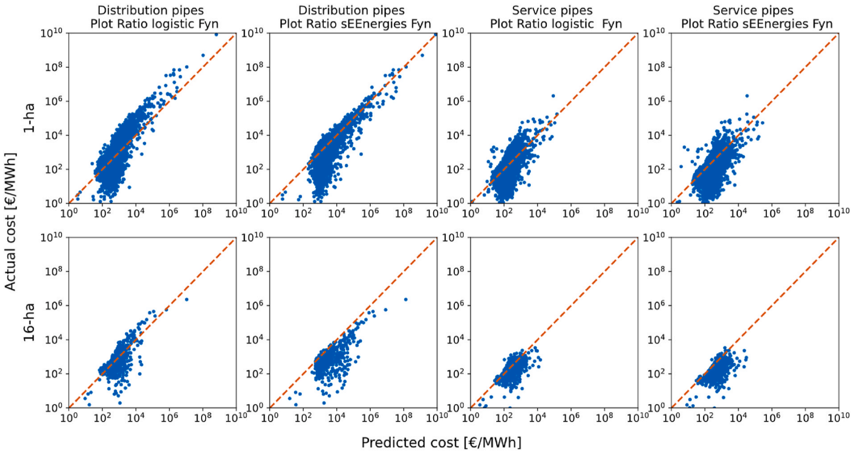

Fig. 9. Predicted vs actual network costs for two different cell sizes in Aarhus.

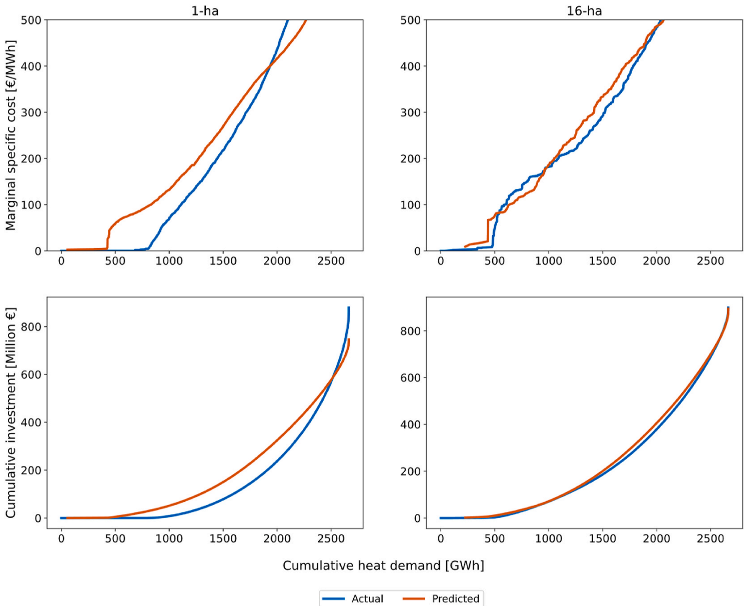

Fig. 10. Predicted vs actual cumulative marginal cost and investment curves in the city of Aarhus.

mere fraction of all the cases analysed, a more comprehensive synopsis of the accuracy of the different equations is shown in Table 3 and Table 4. Each provides the metrics presented in Section 2.6 for the specific network cost and the investment. In these tables, it has only been offered the results obtained with the new equations for the pipe diameter since these are very similar to the results derived from Persson & Werner's equation.

From the analysis of Tables 3 and 4, it is possible to draw five overall conclusions. First, the performance of the models on a cell-by-cell basis is meagre, although there is a sharp difference between the different

Table 3
Goodness of regressions for specific network cost and investment at a resolution of 1-ha.

Regression	Specific Cost				Investment				Common	
	MAE	MDAE	CVRMSE	Area	MAE	MDAE	CVRMSE	Area	ζ	SSPB
	(€/MWh)	(€/MWh)	(−)	(M€)	(€/ha)	(€/ha)	(−)	(M€·GWh)	(−)	(−)
ε - Dist – Logistic	65 745 298	455	955 686%	134	48 403	31 932	105%	110 877	190%	44%
ε - Dist – sEEnergies	826 903 856	850	12 296 354%	1099	128 309	74 888	326%	1 109 988	286%	283%
ε - Serv – Logistic	20 507 091	232	404 369 593%	104	22 216	16 791	97%	45 372	167%	31%
ε - Serv – sEEnergies	8 293 093	242	116 441 933%	166	24 573	17 358	105%	135 556	157%	137%
N - Dist – Logistic	82 784 252	390	1 213 029%	88	44 489	25 450	101%	26 208	246%	54%
N - Serv – Logistic	44 598 538	164	911 831 889%	60	16 775	8536	80%	16 493	143%	14%

Table 4
Goodness of regressions for specific network cost and investment at a resolution of 16-ha.

Regression	Specific Cost				Investment				Common	
	MAE	MDAE	CVRMSE	Area	MAE	MDAE	CVRMSE	Area	ζ	SSPB
	(€/MWh)	(€/MWh)	(−)	(M€)	(€/ha)	(€/ha)	(−)	(M€·GWh)	(−)	(−)
ε - Dist – Logistic	6 976 293	302	4 173 348%	48	20 910	11 537	64%	26 728	70%	17%
ε - Dist – sEEnergies	79 239 954	1122	46 998 291%	1086	95 453	73 596	317%	1 088 679	279%	279%
ε & G - Dist - Logistic	20 998 684	236	17 711 393%	48	22 108	15 405	61%	9565	67%	2%
ε - Serv – Logistic	2 809 717	194	31 783 001%	64	11 554	7534	73%	35 749	90%	31%
ε - Serv – sEEnergies	5 352 940	290	62 996 715%	233	18 624	11 398	119%	168 780	135%	134%
ε & G - Serv – Logistic	18 600 527	146	211 682 008%	55	13 367	11 252	66%	24 402	72%	7%
N - Dist – Logistic	8 948 479	272	5 325 691%	68	18 690	11 370	57%	64 263	71%	17%
N & G - Dist – Logistic	9 155 579	232	6 552 624%	94	18 067	11 375	56%	74 195	68%	6%
N - Serv – Logistic	4 854 850	122	53 830 615%	39	8002	4687	50%	10 892	61%	0%
N & G - Serv – Logistic	4 620 092	104	52 735 999%	42	8125	5599	46%	10 974	53%	−12%

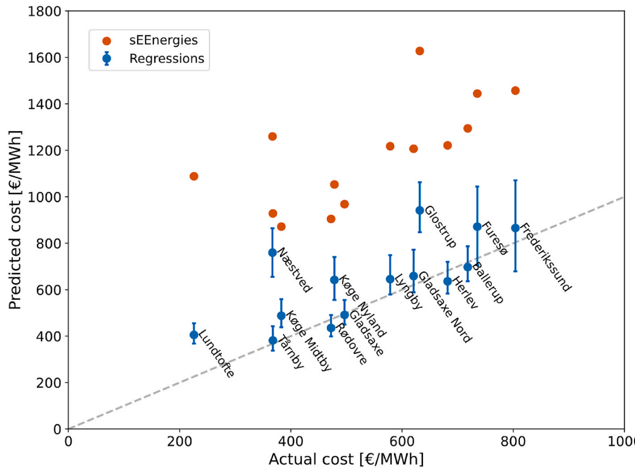

Fig. 11. Predicted vs Actual costs in several areas in Denmark.

specifications. Second, the 16-ha application generally presents lower residuals, following the same trend hinted in prior paragraphs. Third, the error distributions are riddled with outliers, which leads to mean errors being substantially higher than the median errors. A substantial component of this issue is that the model predicts costs in many areas with no district heating pipe, leading to higher values of the parameters. For instance, the median absolute deviation for the first specification in 1-ha cells would nearly halve from 455 €/MWh to 250 €/MWh if those cells were not considered. Fourth, the absolute metrics in the investment calculations tend to be lower than in the specific cost calculation, which could be explained if most outliers happened in areas with low heat demand. This would affect the specific cost but would impact the investment to a much lesser extent. Fifth, all the specifications but one present a positive median bias, i.e., the cost/investment are systematically overpredicted.

A more thorough inspection of the different specifications sheds some light on their relative accuracy. Regarding the new independent parameter, the number of buildings, its benefit depends on the considered pipe type. For the appraisal of distribution pipes at 16 ha, its utilisation does not seem to present a substantial improvement or detriment with respect to the use of the plot ratio. In the specific cost, the MAE, CVRMSE and Area are somewhat higher, but the MDAE is slightly lower. In the investment, the only substantial difference takes place in the area, where the number of buildings is 3 times worse than the plot ratio. The ζ and the bias are nearly identical.

On the contrary, for the evaluation of service pipes, the number of buildings is generally a better predictor than the plot ratio. In this other instance, the MAD of the cost and investment, the ζ, and the SSPB are lower, and the marginal cost and cumulative investment curves are more similar.

Concerning the newly introduced parameter, the Gini coefficient, its utilisation may bring some marginal benefit, but given the added complexity of its computation, it is not likely to be justified.

3.3.3. Validation of model in irregular districting heating areas in Denmark

In addition to the systematic application of Persson & Werner's capital cost model in a homogenous grid, it has also been used in a series of irregularly shaped districts. In these areas, it has been employed both the sEEnergies and the new logistic equations based on the plot ratio. Moreover, Fyn's logarithmic curves were employed for the pipe diameter calculation.

In Fig. 11, where the results have been depicted, it can be appreciated that the sEEnergies curves systematically overestimates the network cost, ranging the predicted values from 80% higher to nearly five times the actual cost. This confirms the conservativeness of the sEEnergies equations. The regression curves provide, on the contrary, network costs much closer to the observed values. Furthermore, in most cases, the actual cost is within the 2σ confidence interval, albeit, in three instances, Lundtofte, Næstved and Glostrup, there is a significant deviation between the predicted and the actual costs.

The deviation stems from the substantial difference in the actual and estimated trench lengths. Whilst in the other cases, the relative error in the pipe length is below 13%, the relative error in these districts ranges from 31% to 45%. Attempts to reveal the origins of this discrepancy have been futile, and no common factor has been found.

4. Conclusions

This study has elucidated the three research questions it endeavoured to explore.

First, the behaviour of effective width, which throughout the course of this work has been investigated by means of its inverse, the specific trench length (L_u), has been unveiled over a wide range of plot ratios for distribution pipes. Hereby, it has been confirmed a lower bound of effective width in high building density areas and the power behaviour in sparse areas. Moreover, the results introduce an upper bound of effective width in very sparse areas.

These findings have enabled the proposal of new equations for estimating the length of distribution pipes that take into account the differentiated behaviour as well as the extension of the model to service pipes and another building density parameter, the specific number of buildings.

Second, it has been disclosed the distinctive behaviour of the average service pipe diameter. Unlike the average distribution pipe diameter, the former remains at a constant low level for a broad range of linear heat densities, and it can vary widely above a threshold of 7 GJ/m.

Third, the capital cost model introduced by Persson and Werner has been improved and validated. This model is in essence a simple but powerful tool to estimate the cost of developing new district heating networks. This improved model can deliver relatively accurate marginal cost and investment curves as well as approximately estimate the network cost of large areas regardless of shape. However, when small areas with few hectares are studied, the investment and especially the specific cost can differ substantially from reality.

Author contributions (by CRediT roles)

1. Luis Sánchez-García: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing – original draft, Writing – review & editing.
2. Helge Averfalk: Conceptualisation, Methodology, Supervision, Writing – review & editing.
3. Erik Möllerström: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.
4. Urban Persson: Conceptualisation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Network data from Aarhus and Fyn as well as the heat demands at building level have been obtained under a confidentiality agreements. Other data are public.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.127427.

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Paper III

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District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth

Mostafa Fallahnejad [a,*], Lukas Kranzl [a], Reinhard Haas [a], Marcus Hummel [b], Andreas Müller [b], Luis Sánchez García [c], Urban Persson [c]

[a] *TU Wien, Institute of Energy Systems and Electrical Drives – Energy Economics Group, Gusshausstrasse 25-29/370-3, 1040 Wien, Austria*
[b] *e-think Energy Research, Argentinierstrasse 18/10, 1040 Wien, Austria*
[c] *School of Business, Innovation and Sustainability, Halmstad University, 301 18 Halmstad, Sweden*

HIGHLIGHTS

- A novel method for analyzing district heating potential in the EU-27 is presented.
- District heating can cover 31% of heat demand (non-industry) in EU-27 up to 2050.
- Grid expansion is needed in economically favorable areas to reduce specific costs.
- A yearly investment of €11.7B at the EU level is required for the grid expansion.

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ABSTRACT

This paper presents a novel approach to modeling the gradual reduction in heat demand and the evolving expansion of district heating (DH) grids for assessing the DH potential in EU member states (MS). It introduces new methodological elements for modeling 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.

1. Introduction

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. District heating (DH) is a technology with both the economic and environmental potential to contribute to the decarbonization of the heating sector in Europe [1] and has therefore been studied from different perspectives.

Sven Werner provides an overview of the district heating and cooling (DHC) in the world [2]. 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) [3] can be considered one of the front-runners for identifying and assessing DH potential in Europe. The project is focussed 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 [4].

Estimating the DH potential through geographic information systems

* Corresponding author.
E-mail address: fallahnejad@eeg.tuwien.ac.at (M. Fallahnejad).

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(GIS) and heat mapping has been practised on different geographical levels. Novosel et al. applied heat mapping to the case study of Zagreb [5]. 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 DHC. In a GIS-based approach, Leurent calculates the linear heat density and DH potential using a heat density map of France [6].

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 [7]. Fallahnejad et al. analyse the impact of transmission and distribution grid costs on DH potential for the case study of Vienna [8]. 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 grid length and heat distribution costs of potential DH systems in Italy [9].

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 [10]. 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 [11]. 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 [12] and in line with Article 14 and Annex VIII of the revised Energy Efficiency Directive [13]. 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 [14]. 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 [15]. 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 modeling for the calculation of the economic DH potential. These studies often use optimization or computational-intensive models and focus on a small area. Marquant et al. propose a clustering approach to analyse DH grid potential, considering both heat supply and demand [16]. Their simplified grid model uses a minimum-spanning-tree algorithm without distinguishing pipe dimensions, while the supply dispatch is calculated in higher detail. Stennikov et al. study the effective heat supply radius for DH systems, focusing on economic efficiency, hydraulic aspects, and supply security [17]. They applied their model to an existing DH grid, identifying effective heat supply radius and weak connections. Röder et al. developed DHNx, an open-source Python library, to analyse the impact of distributed storage systems in DH grid design and their economic benefits related to the piping system [18]. Lumbreras et al. assessed the economic feasibility of DH grids in urban areas, particularly for integrating industrial waste heat sources [19]. They emphasized the importance of data availability for replicability. Jebamalai et al. compared the grid costs of third and fifth-generation DH systems in Kortrijk, Belgium [20]. They concluded that a free low-temperature waste-heat source is essential for the economic implementation of the fifth-generation DH system. Wack et al. developed a non-linear topology optimization model for DH grids [21]. However, applying the model on a larger scale requires the relaxation of the model. 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.

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

- 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 grids 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 [22] or [23] to calculate heat distribution costs. At the same time, the Horizon 2020 project sEEnergies [24] has recently published an updated, validated approach, introducing service pipes in addition to distribution pipes and adapting cost components for each EU member state [25]. The updated approach improves the estimation of the heat distribution costs.
- DH potential and its economic viability in sparse areas have been addressed in Swedish case studies by looking into the sparse district-heating research program of Swedish DH Association [26] or by analyzing the profitability of the sparse DH systems [27]. 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 paper, 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 [28].

Accordingly, the main objectives of this paper 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 modeling 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.

These objectives are followed in the proposed approach and the presentation of the results. The structure of the paper is as follows: Section 2 explains the data and scenarios used for the calculations. Section 3 explains the required step for the implementation of the approach and introduces a new modeling framework. Section 4 presents the results in detail. The results are further discussed in Section 5, and the approach's limitations are enumerated. Section 6 presents our conclusions.

2. 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 paper. These layers were obtained from a report on "renewable space heating under the revised Renewable Energy Directive" published by the European Commission [29]. 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 first broken down to the NUTS 3 levels and subsequently to the hectare level using a number of regional indicators based on the method developed by Müller et al. [30]. The step for breaking demand to NUTS 3 helps to improve the calculation accuracy since certain statistical data, such as building census data, are available at this territorial unit. The breakdown from NUTS 3 to the hectare level assumes that the energy need in a plot area correlates with population, economic activity and climatic conditions in that area, as well as building properties, like the average construction period and volume-to-surface ratios of the buildings.

The EC report introduces five scenarios besides the baseline scenario, focusing on direct RES heating, electrification, e-fuels, hydrogen and DH [29]. 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 paper are based mainly on the best-case scenario.

Fig. 1 shows the useful 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 3128.8 TWh in 2020 to 1709.1 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 [31] (Corresponding data of BL2050 scenario is available in [32]). The BL2050 scenario is an adapted version of the PRIMES scenario for 2050 [33,34]. Based on this scenario, the heat demand in EU-27 countries should reduce to 2088.7 TWh, 379.6 TWh higher than 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, presented in Fig. 2, 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.

The DH shares within DH areas in 2050 are educated anticipations in alignment with current levels from mature DH markets (e.g., 2020's shares in Denmark and Sweden as shown in Fig. 2) and reflect levels which facilitate cost-effective heat distribution.

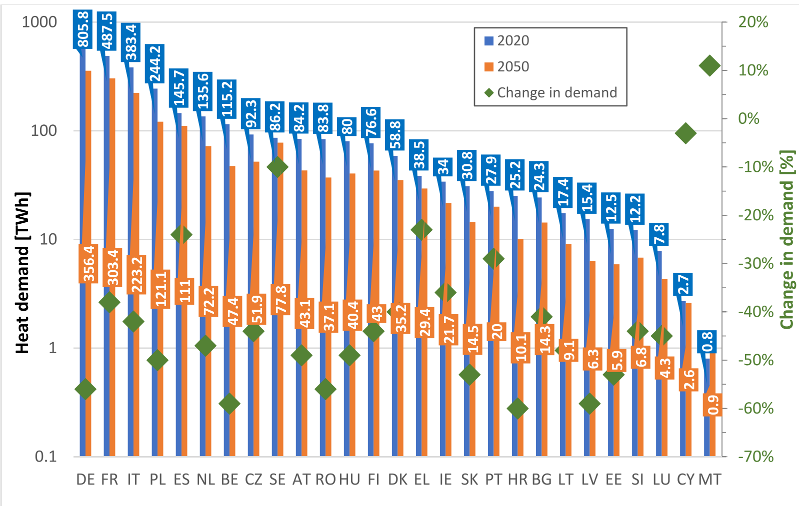

Fig. 1. Useful heat demand levels (TWh) in 2020 and 2050, and the relative changes in residential and tertiary sectors (secondary Y-axis) based on the best-case scenario.

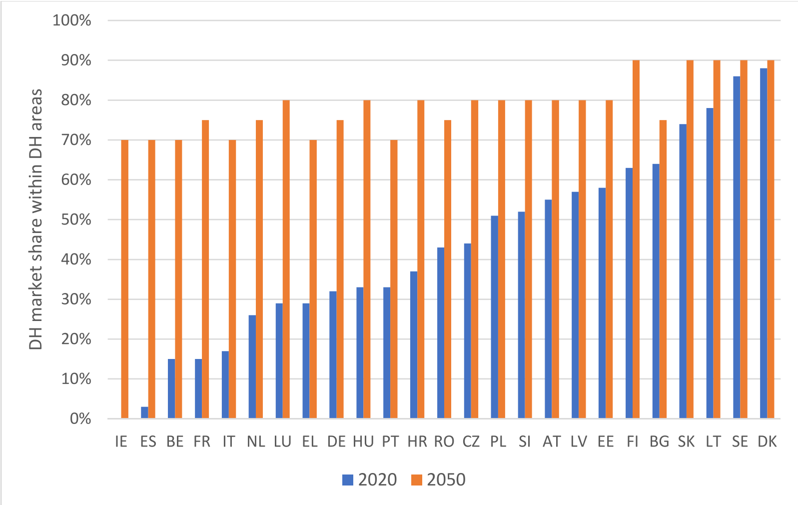

Fig. 2. DH market shares within DH areas used as inputs for the base year (2020) and target year (2050).

3. Method

This section 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 paper, 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 paper, 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 paper, we use “DH market share” or “DH market share in DH areas” 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. Section 3.3 elaborates the approach for the identification of the DH areas.

3.1. Heat distribution costs under 100% of market share in DH areas

In this section, we introduce a model for assessing the capital cost of DH grids in a national context and identifying the potential DH areas accordingly.

Persson et al. introduced a methodology to estimate the DH heat distribution costs [22,23]. Their methodology uses several independent input data, such as pipe diameter, construction costs, interest rate, and demographic data. Fig. 3 shows the 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 section, 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 grid investment cost is the linear heat density, 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. (1).

$$LinearHeatDensity = Q_T/L \; [GJ/(m.a)] \quad (1)$$

Persson and Werner use demographic data to calculate the linear heat density analytically. The calculation procedure is shown in Eqs. (2) to (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 [35]. The approach has been used widely and the formulation updated a few times with the grid data of different cities. The sEEnergies project addresses one of the most recent updates [24] and provides formulations for the distribution and service pipes. The proposed update is the basis for the calculations performed in this paper. The effective width of the DH distribution grid can be obtained using Eq. (5). As Eq. (5) shows, the effective width is assumed to be constant in areas with plot ratios above 0.1353 (hereon, “high plot ratio areas”).

$$q = Q_T/GFA \; \left[GJ/\left(m^2{\cdot}a\right)\right] \quad (2)$$

$$q_T = Q_T/A_L \; \left[GJ/\left(m^2{\cdot}a\right)\right] \quad (3)$$

$$LinearHeatDensity = \frac{Q_T}{L} = pr{\cdot}q{\cdot}w = q_T{\cdot}w \; [GJ/(m.a)] \quad (4)$$

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

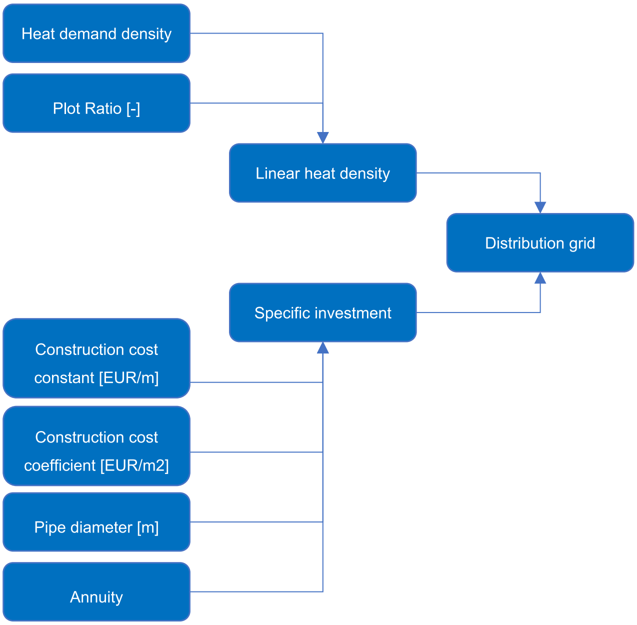

Fig. 3. Schematic overview of the procedure to calculate DH distribution grid capital costs.

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 20 mm.

$$d_{a,DistributionPipe} = \begin{cases} 0.02, Q_T < 1.5\ GJ \\ 0.0486 \cdot ln(Q_T/L) + 0.0007, Q_T \geq 1.5\ GJ \end{cases} [m] \tag{6}$$

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. (7). An average diameter of 30 mm 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 20 mm.

$$w_{ServicePipe} = A_L/L = \begin{cases} e^2/pr\ [m]\ 0 < pr \leq 0.1353 \\ e^{\frac{ln(pr)+3.5}{0.7737+0.18559 \bullet ln(pr)}}\ [m]\ pr > 0.1353 \end{cases} \tag{7}$$

$$d_{a,ServicePipe} = \begin{cases} 0.02, & Q_T < 1.5\ GJ \\ 0.03, & Q_T \geq 1.5\ GJ \end{cases} [m] \tag{8}$$

The specific grid investment cost (I/L) of both distribution and service pipes can be derived using Eq. (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/m^2, respectively. The parameters C_1 and C_2 are obtained empirically based on the existing grids. Persson et al. calculate these factors for each EU member state [25]. These values are provided in the Appendix of this paper in Table A.1.

$$\frac{I}{L} = C_1 + C_2 \cdot d_a \left[\frac{€}{m}\right] \tag{9}$$

The specific cost of heat distribution ($Cost_{HeatDistribution,T}$) for each unit of delivered heat in year T can be obtained from Eq. (10). The annuity factor is obtained based on the interest rate (r) and the depreciation time (n) in years.

$$Cost_{HeatDistribution,T} = \frac{a.I}{Q_s} = \frac{a.\left(\frac{I}{L}\right)}{\left(\frac{Q_s}{L}\right)} = \frac{a}{q_{s,T}} \bullet \left(\frac{C_1 + C_2 \bullet d_{a,DistributionPipe}}{w_{DistributionPipe}} + \frac{C_1 + C_2 \bullet d_{a,ServicePipe}}{w_{ServicePipe}}\right) \left[\frac{€}{GJ}\right] \tag{10}$$

$$a = \frac{r\cdot(1+r)^n}{(1+r)^n - 1} \tag{11}$$

3.2. Heat distribution costs under evolving DH 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. In this section, the equations provided in the previous section 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. (12). This equation leads to slightly higher heat demand reductions at the beginning of the study horizon and lower reductions near the end.

$$D_t = D_0 \bullet \sqrt[m]{(1 - D_m/D_0)^t} \tag{12}$$

$$t \,\epsilon\, T = \{0, 1, 2, \ldots, m\} \tag{13}$$

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. (14).

$$Q_t = D_t \bullet \left[MS_0 + t \bullet \frac{MS_m - MS_0}{m}\right] \tag{14}$$

The formulation of the effective width in Eqs. (5) and (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. We therefore focus 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 [15]. 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. (15).

$$L = l/2 = 65.3 \bullet ln(N_{buildings}) - 42.25 \tag{15}$$

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

$$L = 65.3 \bullet ln(MS \bullet N_{buildings}) - 42.25 \tag{16}$$

$$L = A_L \bullet pr \bullet AdjFactor/e^2 \tag{17}$$

$$AdjFactor = f(MS) \tag{18}$$

$$0 < AdjFactor \leq 1 \tag{19}$$

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. (20).

$$\frac{L_{\alpha\%}}{L_{100\%}} = \frac{AdjFactor \bullet pr}{pr} = AdjFactor \tag{20}$$

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

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

The number of buildings within each hectare of EU-27 countries

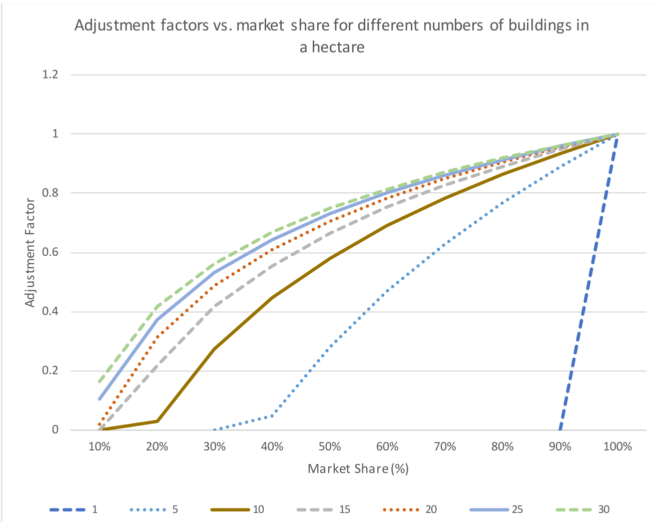

Fig. 4. Adjustment factors as a function of DH market shares for different numbers of buildings in a hectare.

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. We consider a minimum adjustment factor of 0.0279 for market shares below 20%. The fitted logarithmic trendline is provided in Eq. (21).

$$AdjFactor = \begin{cases} 0.0279, & MS < 20\% \\ 0.604 \cdot ln(MS) - 1.7815, & MS \geq 20\% \end{cases} \tag{21}$$

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 behavior 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 41.53 m. The effective width formulations of distribution and service pipes are provided in Eq. (22) and Eq. (23), respectively.

$$w_{DistributionPipe} = A_L/L = \begin{cases} e^2/(AdjFactor \bullet pr)\ [m]\ 0 < pr \leq 0.1353 \\ e^4\ [m]\ pr > 0.1353 \end{cases} \tag{22}$$

Table 1
Input parameters for the study of the impact of the adjustment factor.

Parameter	Value	Unit
Heat density in the DH area	100 (for 4.1.1) & 500 (for 4.1.2)	MWh/ha
Construction cost constant (C1)	212	EUR/m
Construction cost coefficient (C2)	4464	EUR/m^2
Depreciation time	40	Year(s)
Interest rate	2	%

The method explained in this section has been fully implemented in Python and published with an open-source license [37].

4. Results

The results section is composed of three sub-sections, 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.

4.1. The impact of the adjustment factor

This section 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 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.

$$w_{ServicePipe} = A_L/L = \begin{cases} e^2/(AdjFactor \bullet pr)\ [m]\ 0 < pr \leq 0.1353 \\ e^{\frac{ln(AdjFactor \bullet pr)+3.5}{0.7737+0.18559 \bullet ln(AdjFactor \bullet pr)}}\ [m]\ (pr > 0.1353) \wedge (pr \bullet AdjFactor > 0.1353) \\ 41.53\ [m]\ else \end{cases} \tag{23}$$

Considering the annual evolution of both heat demand and DH market share, the specific cost of heat distribution ($Cost_{HeatDistribution}$) is obtained by Eq. (24). It is assumed that after the target year (m), the heat demand and supplied heat by DH remain constant.

$$Cost_{HeatDistribution} = \frac{1}{\sum_{t=0}^{m} q_{T,t} \bullet (1+r)^{-t} + \sum_{t=m}^{n} q_{T,m} \bullet (1+r)^{-t}} \bullet \left(\frac{C_1 + C_2 \bullet d_{a,DistributionPipe}}{w_{DistributionPipe}} + \frac{C_1 + C_2 \bullet d_{a,ServicePipe}}{w_{ServicePipe}} \right) \left[\frac{€}{GJ}\right] \tag{24}$$

The impact of the adjustment factor will be presented in Section 4.1.

3.3. Identification of DH areas

For the identification of potential DH areas, the proposed approach by Fallahnejad et al. is used [36]. 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.

Both the above conditions, directly and indirectly, are related to the heat demand. The best-case scenario from [29] includes a dramatic heat demand reduction. Therefore, the approach is also applied to the baseline scenario obtained from [32]. Finally, the DH potentials obtained from each scenario are compared.

4.1.1. 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 section, 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 behavior 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 behavior.

Fig. 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.

Linear heat density and the average pipe diameter have similar behavior, as shown in Fig. 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

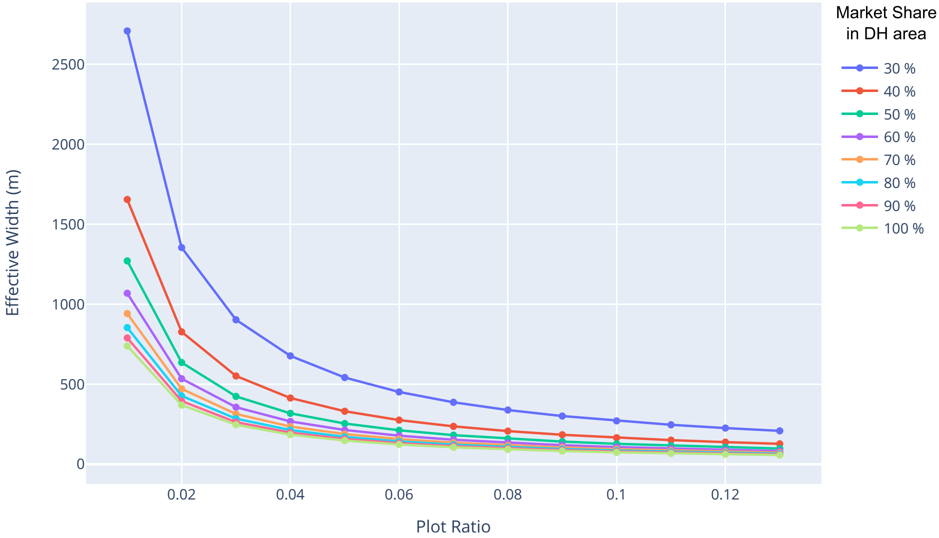

Fig. 5. Effective width of distribution pipes versus plot ratio for different DH market shares.

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.

Fig. 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.
- 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.

4.1.2. Service pipes and high plot ratio area

Based on Eq. (21), a minimum adjustment factor of 0.0279 for market shares below 20% was considered. As can be seen in Fig. 8, Fig. 9 and Fig. 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%.

4.2. DH potential in EU-27 countries

The calculation for the identification of potential DH areas is conducted with an interest 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 B.1 in the appendix of this paper. 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 km^2. The identified DH areas in this paper cover 24.5% of the residential areas (=28,911.4 km^2) 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 favorable 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.

Fig. 11 illustrates the average heat densities within the identified DH

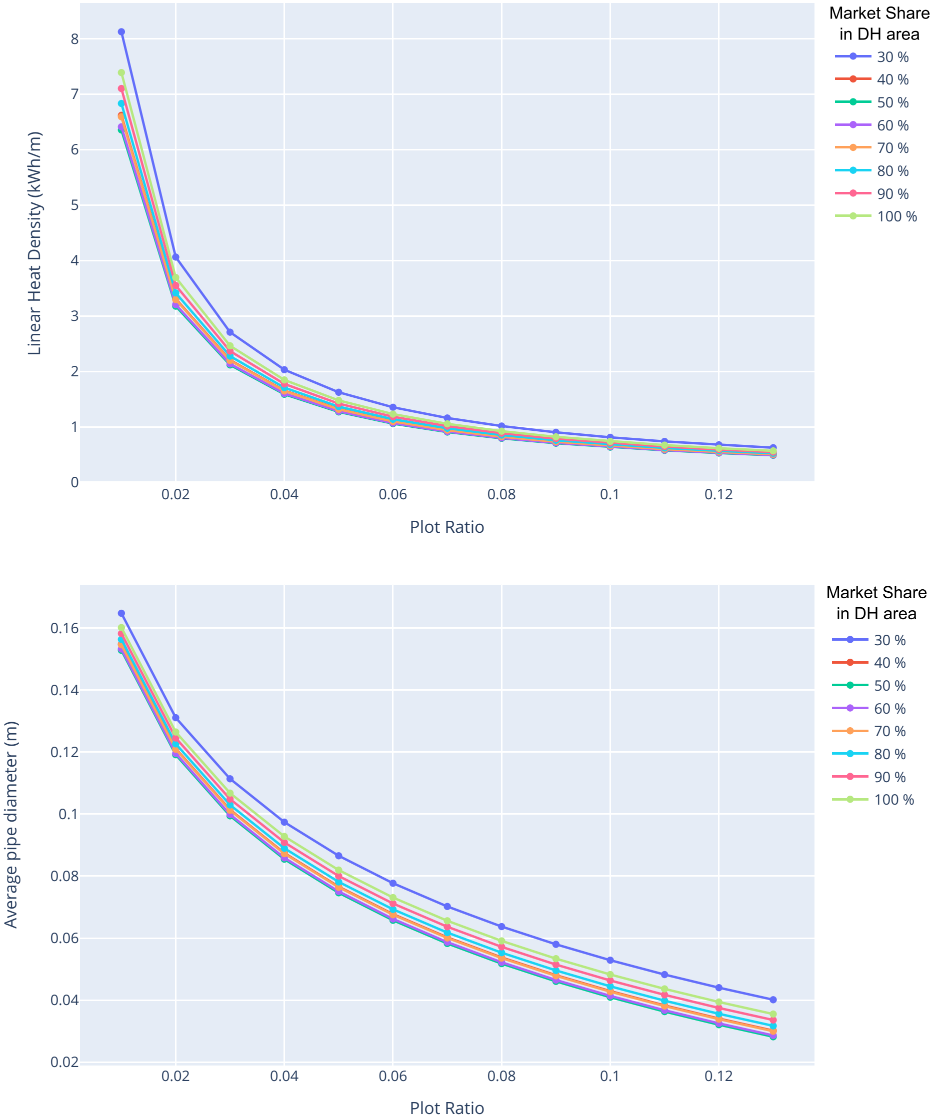

Fig. 6. Linear heat density (top) and average pipe diameter (bottom) of DH distribution pipes versus plot ratio for different DH market shares.

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 favorable 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.

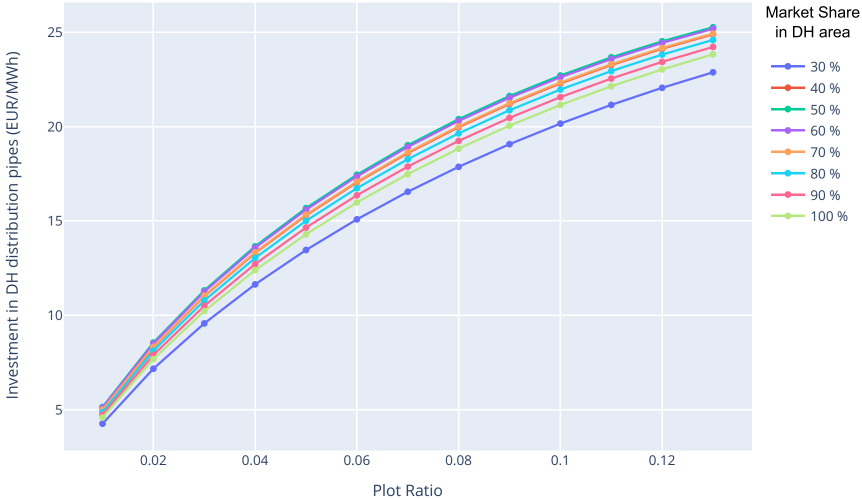

Fig. 7. Specific investment costs of the DH distribution pipes versus plot ratio for different DH market shares.

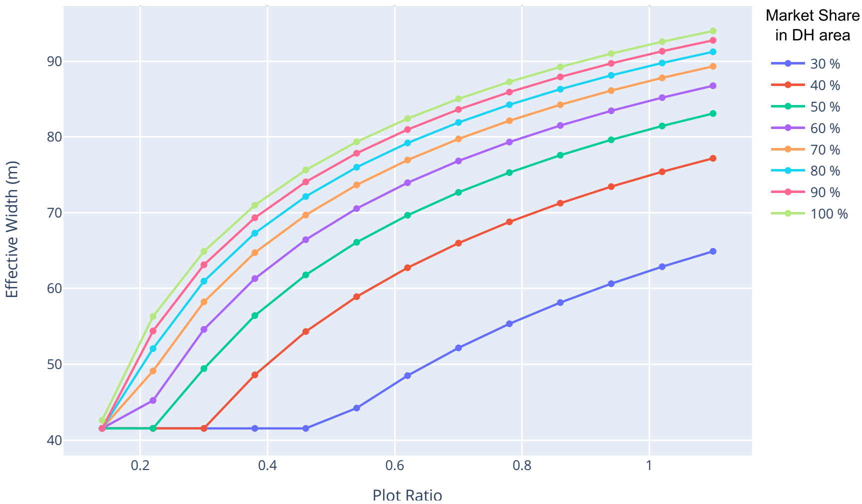

Fig. 8. Effective width of service pipes versus plot ratio for different DH market shares.

As illustrated in Fig. 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 consider it as a potential DH area. For example, an average heat demand density of 215 MWh/ha in an are within Austria is generally a necessary condition to fulfil other mentioned constraints in this paper for identifying potential DH areas.

4.3. DH grid costs

The calculations performed in this paper 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

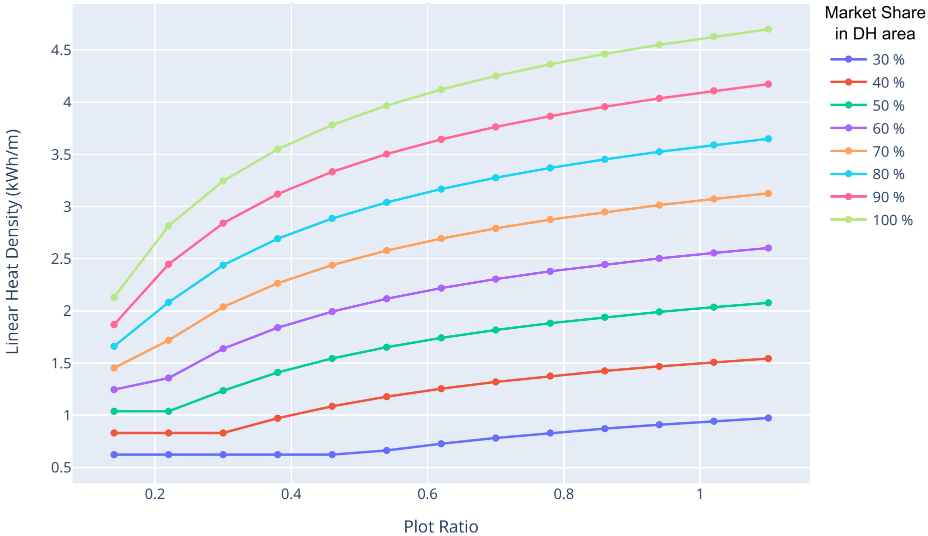

Fig. 9. Linear heat density of DH service pipes versus plot ratio for different DH market shares.

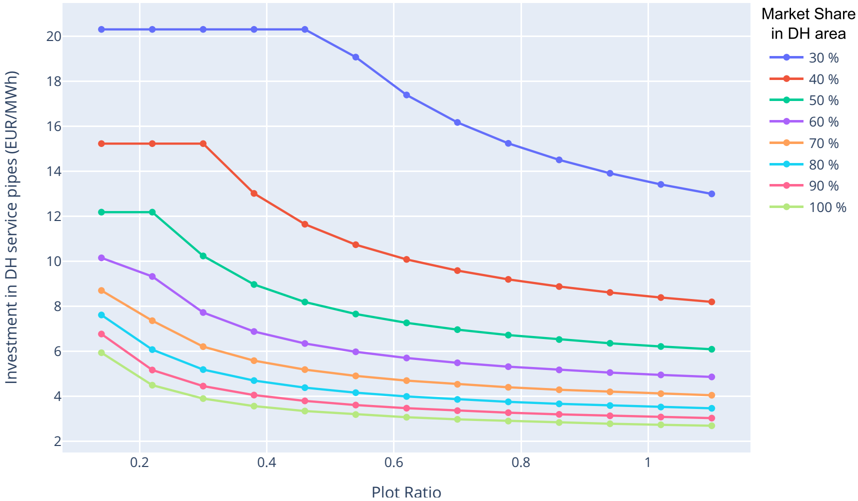

Fig. 10. Specific investment costs of the DH service pipes versus plot ratio for different DH market shares.

pipes. Table 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.

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 B.1, 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. (24). Accordingly,

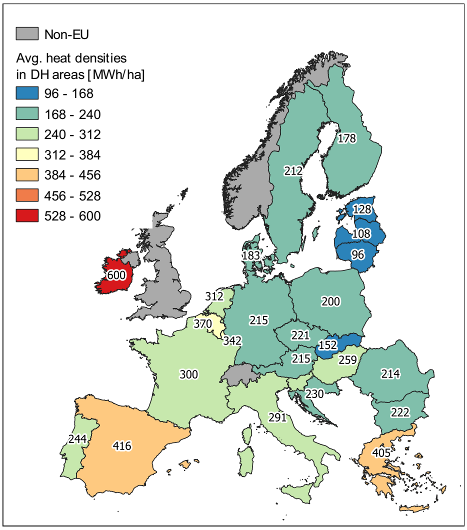

Fig. 11. Average heat densities in identified DH areas based on Best-Case scenario.

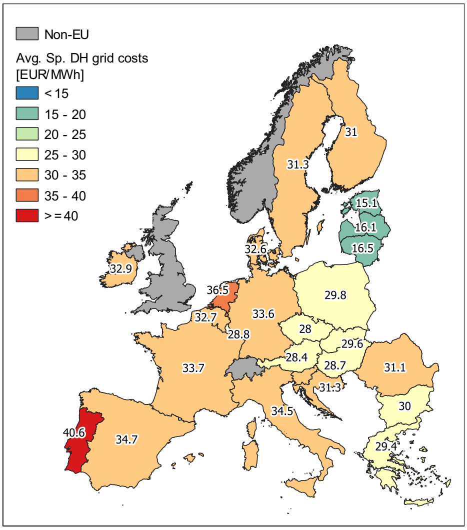

Fig. 12. Average specific DH grid costs based on Best-Case scenario.

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 and 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 Fig. 12.

4.4. Synthesis of DH 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
- $\geq$ 35 EUR/MWh

Fig. 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

Table 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	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	**IE**	0%	70%	9.9
BE	15%	70%	130.8	**IT**	17%	70%	1215.6
BG	64%	75%	114.0	**LT**	78%	90%	78.1
CY	0%	0%	0.0	**LU**	29%	80%	37.5
CZ	44%	80%	443.2	**LV**	57%	80%	55.6
DE	32%	75%	2675.4	**MT**	0%	0%	0.0
DK	88%	90%	482.2	**NL**	26%	75%	384.2
EE	58%	80%	42.7	**PL**	51%	80%	1116.6
EL	29%	70%	106.7	**PT**	33%	70%	59.8
ES	3%	70%	471.2	**RO**	43%	75%	234.5
FI	63%	90%	675.4	**SE**	86%	90%	1129.0
FR	15%	75%	1461.0	**SI**	52%	80%	29.1
HR	37%	80%	57.1	**SK**	74%	90%	146.2
HU	33%	80%	248.7				
	TOTAL yearly cashflow on EU-27 level:					**11,734 MEUR**	

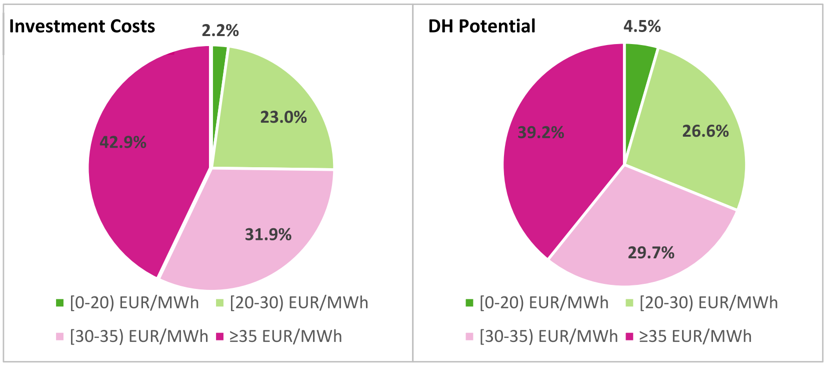

Fig. 13. Share of investment costs (left figure) and share of DH potentials (right figures) corresponding to each average specific DH grid cost category (EU-27).

specific DH grid costs result from low starting market shares or high construction costs (see Appendix) 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.

Fig. 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.

The distribution of DH potential between different cost categories is not uniform in the member states. Fig. 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 Fig. 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 favorable condition for DH expansion in Baltic and Eastern European countries. Favorable 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

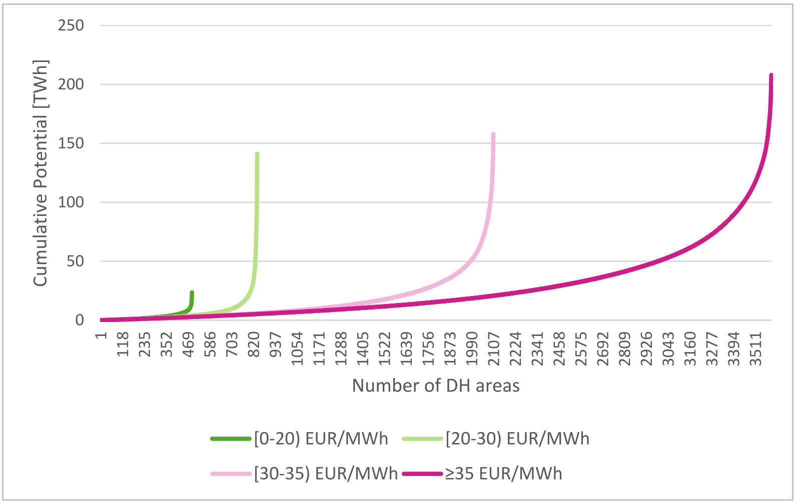

Fig. 14. Cumulative DH potential of each average specific DH grid cost category (EU-27).

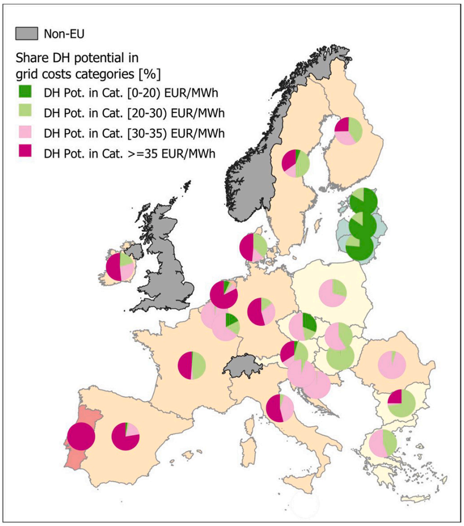

Fig. 15. Share of DH potentials corresponding to average specific DH grid cost categories in EU member states.

areas is the main reason for costs above 35 EUR/MWh in France, Italy, and Spain. In France, however, >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.

4.5. Impact of higher heat demand in 2050 on DH potentials

This section 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 [31,32]. 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 section 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 paper.

A summary of the obtained results for the BL2050 scenario is provided in Table B.2 in the appendix of this paper. 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.

5. Discussion of results and limitations

The proposed method in this paper 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. (12) and Eq. (14),
- The DH market share evolution was considered uniformly for all hectare cells of each in a country.
- For the adjustment factor:
  - o 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),
  - o 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 paper 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. (22) and Eq. (23)). The adjustment factor allows the modeling 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 Fig. 7; however, the specific distribution costs are close to each other at a given plot ratio. On the other hand, Fig. 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 [30], 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 paper, ensures that no overestimation for 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 B.1, the construction cost constant (C_1) and construction cost coefficient (C_2) in each country were considered. Looking at the columns for "Average specific DH grid cost in all DH areas over the lifetime" in Table B.1 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 overdimensioned 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 paper. 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 for the case of Austria [12].

6. Conclusions

DH grids are not built all at once. The expansion of DH grids is a gradual process. This paper used the existing theoretical framework of modeling heat distribution costs of DH systems and introduced an approach for modeling 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 paper 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 [31]. 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 favorable areas, and supply levels should be maintained or increased. In this paper, 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 11.7 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 average specific heat distribution costs 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 grids and achieving sufficiently high DH market shares within DH areas. This is achievable under favorable financial and political support schemes, such as DH zoning, for DH.

CRediT authorship contribution statement

Mostafa Fallahnejad: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Lukas Kranzl:** Supervision, Writing – review & editing. **Reinhard Haas:** Supervision, Writing – review & editing. **Marcus Hummel:** Conceptualization, Validation. **Andreas Müller:** Data curation. **Luis Sánchez García:** Conceptualization, Methodology, Validation, Writing – review & editing. **Urban Persson:** Writing – review & editing, Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The input and output data are provided in [38].

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Appendix A

Table A.1 shows the construction cost constants and coefficients in different EU-27 countries. These values are obtained from the sEEnergies project [24]. 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 B

Input parameters and obtained calculation results for the EU-27 countries for the best-case and BL2050 scenarios are summarized in Table B.1 and Table B.2, respectively.

Fill color	Description
(yellow)	Input
(blue)	Output
(green)	EU-27
(grey)	Not Relevant/Applicable

Table B.1
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%
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%
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 B.2
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%
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%**

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Paper IV

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Feasibility of district heating in a mild climate: A comparison of warm and cold temperature networks in Bilbao

Luis Sánchez-García [a,*], Helge Averfalk [a], Nekane Hermoso-Martínez [b], Patxi Hernández-Iñarra [b], Erik Möllerström [a], Urban Persson [a]

[a] School of Business, Innovation and Sustainability, Halmstad University, PO BOX 823, SE 30118 Halmstad, Sweden
[b] TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, 48160, Derio, Spain

HIGHLIGHTS

- Comprehensive comparative analysis of various district energy network configurations.
- District energy is feasible compared to air-source heat pumps in Southern Europe.
- Low-carbon heating is not viable if the carbon costs of fossil fuels are not internalised.
- Warm networks are more cost-effective than cold networks for heat supply.
- Cold networks are nearly cost-equivalent with warm networks for combined heating and cooling.

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ABSTRACT

District heating and cooling systems can aid in decarbonisation and the provision of efficient heating and cooling in Europe. However, whereas these systems have achieved high penetration rates in colder climates of Northern, Central and Eastern Europe, they remain marginal in milder climates of Southern Europe. In terms of network design, district heating and cooling systems can be configured in different ways. In so-called warm networks, the required temperature for all the consumers is attained city-wide, and in so-called cold systems, the necessary temperature is achieved at the consumers' premises by ancillary equipment. The most cost-effective heating and cooling solution for urban areas requires investigation. This research models and compares cold and warm district energy systems with other heating and cooling solutions through a comprehensive case study executed in the city of Bilbao, Spain. The city is characterised by a mild climate and a high population density which is characteristic of many Southern European cities. The results show that district energy systems are economically advantageous compared to other low-carbon solutions, such as air-source heat pumps. However, these systems are not able to outcompete natural gas under current cost and taxation levels. Warm networks provide a cheaper source of heat compared to cold networks, but both network types lead to similar expenditures for combined heating and cooling supply. This paper, presents the study context and its results, and is complemented by an exhaustive detailed methodology document and a separate supplementary material repository.

1. Introduction

Climate change and the ongoing energy crises necessitate decarbonization of the entire energy system [1], including the non-industrial heating and cooling sector. This sector accounts for a third of Europe's final energy demand [2] and is still highly reliant on fossil fuels [3].

To tackle these challenges and achieve heat supply decarbonization by 2050, the *Decarb City Pipes 2050* project [4,5] has fostered collaboration between seven European cities: Bilbao, Bratislava, Dublin, Munich, Rotterdam, Vienna, and Winterthur. These cities have developed roadmaps, generally including a combination of heat savings, individual[1] heating solutions in sparse areas, and an expansion and

* Corresponding author.
E-mail address: luis.sanchez_garcia@hh.se (L. Sánchez-García).

[1] The term individual refers to heat solutions with production for the entire building, centralised heating, or within each single dwelling or flat, which is the most common form of heating in Spain. This usage differs from the Spanish norm, where it usually refers only to flat solutions.

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decarbonization of district heating (DH) in the densest areas.

Unlike other continental project participants, the city of Bilbao was not equipped with a district heating system until the recent construction of a geothermal cold system on the island of Zorrozaurre [6]. This contrasts with its well-developed gas grid, which traces its origin back to 1848 [7]. Moreover, similarly to most cities in Spain [8], the city's heat demands are met primarily by fossil fuels such as natural gas (70 %), heating oil (10 %), and bottled LPG (2 %), whereas electricity delivers the remaining 18 %.

Moreover, the city is characterised by a milder climate than its project counterparts, with 1584 annual degree days [9] and a heating index of 71 compared to the European average of 100 [10]. However, it has a high population density of 54 700 inhabitants/km^2 [11,12] which is similar to other Spanish cities [13–15] but much higher than the other city partners.[2] These factors balance with one another, leading to very similar heat demand densities to the other cities [16,17]. In principle, this means that the city is ideal for the development of district heating [18].

1.1. The Spanish context

Despite this apparent viability for district heating, these systems currently deliver a tiny fraction of the heat demand in the Spanish residential and service sectors, as illustrated in Fig. 1. Furthermore, Spanish policy makers, civil servants, practitioners, and academics often assert that district heating and cooling systems are ill-suited to the country due to its milder climate compared to Scandinavia or Eastern Europe, where these systems fulfil a higher share of the heat demand. They also argue that these systems lack a suitable legal framework, that new utilities are difficult to install in urban environments, and there is a general lack of experience and awareness. The public energy debate in the country either neglects the importance of the heating and cooling sector or circumscribes the decarbonization options to heat pumps or renewable gases such as biomethane or hydrogen on the supply side and space heating demand reductions.

Furthermore, unlike other countries such as Denmark, with a long tradition of local energy planning [19,20], Spain has limited experience in municipal heating and cooling solutions beyond natural gas networks. The recently energy efficiency directive recast [21] compels municipalities above 45 000 inhabitants to prepare local heating and cooling plans. In this context, an accurate appraisal of the economics of conventional and low-carbon solutions becomes necessary.

Moreover, there is limited research on the economic benefits of district heating in Spain in relation to other decarbonization options, albeit two European projects (Heat Roadmap Europe and sEEnergies) have suggested high potential market shares [22,23]. Most research has focused on studying the district heating potential from a business perspective without comparison to other means of decarbonization. Matas-Escamilla and Menéndez [24,25] investigates the business economy of geothermal district heating in rural areas located in Northern Spain. Similarly, other research [26–28] analyses the potential for district heating based on various types of renewable energy sources and Lumbreras' study [29] revolves around the use of industrial waste heat in the city of Vitoria. Only one study [15] compares the levelized cost of district heating directly with other sources.

1.2. Network configurations

District heating can take a variety of shapes depending on the system temperatures and the location of heat and cold production. Werner has identified six main configuration groups [32], which may be broadly classified into two categories: warm and cold networks. While the former can deliver all the heat needs at the buildings, the latter will demand some ancillary heat supply at the customer premises (such as heat pumps).

Cold networks have received growing attention from researchers over the last decade; Buffa, Averfalk, and Pellegrini have published reviews on the topic [33–35]. Early examples and proposals of these systems are provided by Dutz in Germany [36] and Rybach in Switzerland [37], and more recent applications include the Mijnwater project in the Netherlands [38], the London South Bank University [39], and a home cooperative in Zürich [40].

Buffa et al. argue that these systems may enable the recovery of low-temperature waste and renewable heat, may simultaneously provide heating and cooling, be modular, and may have negligible heat loss (thanks to the low temperature difference and despite the utilization of uninsulated pipes). However, they also warn that the higher investment costs for consumer heat pumps, the larger required pipes, and the higher pumping costs may jeopardize their implementation. A concrete example of the potential of these systems is provided by Volkova et al. [41], who analyses the potential in the Baltic countries.

Various authors have analysed cold networks from different standpoints, such as optimization methods, impacts of different system parameters, or the potential of these systems.

Examples of the first perspective are provided by Wirtz, who presents a Mixed Integer Linear Programming problem for optimising a cold network with district-wide heat production and building booster heat pumps [42]. The buildings are optimised simultaneously in a series of design days. Wirtz extends their previous model [43] to take temperature into account, and, more recently, they expand their model to multi-period optimization [44].

Concerning the impact of system parameters, Millar analyses the impact of distributed thermal energy storage, energy sharing, a carbon tax, and different electricity tariffs in a cold district heating system [45]. Energy storage was vital to drive the costs down as well as to facilitate energy sharing between buildings. Moreover, they show that the electricity tariff significantly impacts costs and the operation strategy. With a similar perspective, Edtmayer [46] studies the sector coupling potential of a cold district heating system in Zürich by exploiting the buildings' thermal inertia.

From a business standpoint, Calise et al. analyse two cold networks located in Southern Europe based on seawater and shallow geothermal energy using detailed simulations in TRNSYS [47,48]. In both cases, they reached long payback times (relative to conventional gas boilers), although the results are highly sensitive to the amount of self-produced electricity.

An issue with prior studies by Calise et al. is that they do not analyse cold networks compared to warm, conventional district heating systems. Hence, it is not possible to conclude whether a warm district heating solution would be more feasible. This problem is addressed from two different angles by three sets of studies carried out by Lund et al., Trier et al., and Guðmundsson et al.

The first is the energy system perspective taken by Lund et al. [49], who consider different district heating options such as conventional, low-temperature, and cold networks with various types of temperature boosting. They conclude that the low-temperature warm district heating is the heat solution with the lowest socio-economic cost.

The second is the district heating system viewpoint taken by Trier and Guðmundsson. The former calculates the annual cost of a warm district heating with cold supply at a building level and a cold network in the Flexynets guidebook [50]. The yearly outlays for the conventional solution are substantially lower, but the difference steadily disappears as the cooling demand increases. Nevertheless, no district-wide cooling production is considered. The latter initiates [51] and later expands [52] a Levelized Cost of Heat comparison between a low-temperature warm district heating system and various cold networks with different temperature sources in two suburban areas (one in Denmark and another in

[2] Based on population-weighted population density. The other participating cities have densities ranging from 7200 p/km^2 in Winterthur to 24 300 p/km^2 in Vienna.

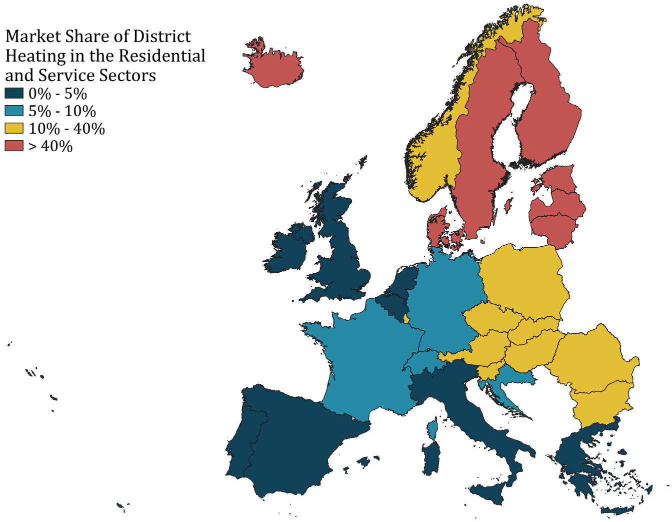

Fig. 1. District Heating market shares in Europe [30,31].

the United Kingdom). Given the climatic conditions of the regions, only heating is considered. In both cases, the cold systems lead to the highest costs due to the installation of heat pumps in buildings and operation outlays. More recently, Guðmundsson analyses [53] a case study in Rome. Like the Northern Europe studies, they conclude that the conventional warm district heating solution is more cost-effective.

1.3. Aim and scope

This research aims to address the gaps identified in the literature described hereunder.

First, existing research on cold district heating has chiefly focused on its qualitative advantages and disadvantages compared to conventional warm district heating, and only two studies have aimed to take them up from a quantitative perspective. However, that research investigated suburban areas in Northern Europe, which are not the prime target for district heating expansion. This novel study will examine the economics of warm and cold district heating in an urban core characterised by a mild climate. Given the growing interest in district heating as a tool for decarbonizing the heating sector, this study may offer guidance to researchers, practitioners, and policy makers on the most suitable district heating solution.

Second, thus far the available literature on Spain has ineffectively addressed the competitiveness of district heating and cooling relative to individual low-carbon heating solutions like building or flat heat pumps. This study will not only compare five district heating solutions but will also include other decarbonization options, as well as conventional heating and cooling options. In this sense, this research may contribute scientific evidence to a more factual public discussion on the pros and cons of the various paths available in decarbonising the heating sector in countries with scant district heating traditions.

Third, this article presents a comprehensive modelling architecture, utilising a mixture of methods. Among others, these methods will determine heating and cooling demands and loads, evaluate network sizing, and assess heat and cold supply and storage options. While it builds on previous research it is original in many ways. Furthermore, this architecture is complemented by exhaustive data gathering from original sources on the installation costs of heating and cooling elements. Although the approaches and data are applied to a specific case study they can be employed in other situations. Furthermore, although the research is focused on the case study of the city of Bilbao, the results are discussed in a broader context, making them relevant beyond the confines of the city.

To address the three research gaps, this study is structured around the following research questions:

1. Is a district energy solution economically feasible in a mild climate?
2. How do different district energy configurations compare to one another and to other heating and cooling solutions in terms of cost-efficiency?

Concerning alternative heating options to district heating, only air-source heat pumps and natural gas boilers are considered. Although there would theoretically be other means of decarbonization, such as geothermal heat pumps, solid biomass, biomethane or hydrogen boilers, either at building or flat levels, these are not considered in this study. The high heat demand density would not allow a large-scale deployment of shallow geothermal heating [54] and solid biomass would have negative consequences in the city's air pollution. Furthermore, biomethane is too limited in potential, which would encourage its use in other sectors. Lastly, the use of hydrogen in the heating sector would require a drastic increase in renewable electricity production due to its low-conversion efficiency [55].

The scope of this study will also be limited to an economic analysis under the current framework conditions. Furthermore, it will be assumed that the different heat production infrastructure can be installed with no electricity grid reinforcements and no additional impacts on the energy system. In addition, it is assumed that there are no hard constraints on carbon emissions for the low-carbon solutions discussed, taking the implicit assumption that the electricity grid will eventually decarbonise. Other relevant factors such as material depletion, exergy destruction, or second-order impacts (e.g., tax revenue

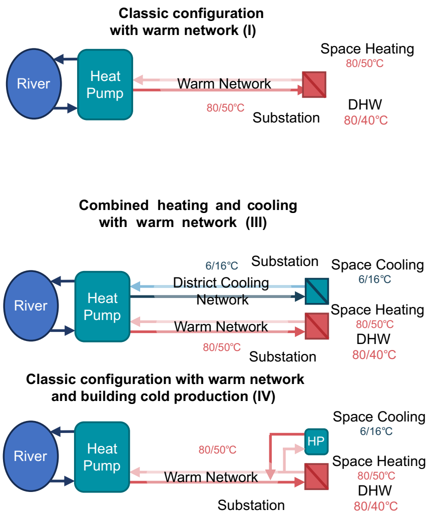

Fig. 2. Configurations of heat and cold supply for warm and cold district heating.

changes) are not considered.

This paper is structured as follows: Section 2 presents the methodology and the data used in the study; this is followed by an exposition of the intermediate and final results in Sections 3 and 4, respectively. Finally, the results are discussed in Section 5, and conclusions are reached in Section 6.

1.4. Definitions

Following the definitions elaborated by Werner [32], this article analyses five types of district heating systems, which are illustrated in Figure 2.

I. Classic configuration with warm network. This option represents a conventional district heating network with high-temperature district-wide heat production. For simplicity, it will also be referred to as warm district heating.
II. Ultra-low configuration with cold network. This solution consists of a non-insulated two-pipe network that distributes energy at temperatures near ambient temperature. Each building is equipped with a heat pump capable of boosting the heat for space heating and domestic hot water. For simplicity, it will also be referred to as cold district heating.
III. Warm combined heating and cooling configuration with warm network. Heat and cold are produced on a city level, possibly in synergy. A conventional district cooling two-pipe network is constructed in parallel to the conventional district heating network. For simplicity, it will also be referred to as warm district heating with district cold production.
IV. Classic configuration with warm network and building cold production. In this option, building chillers deliver cooling to each building, and the waste heat is distributed through the conventional district heating. For simplicity, it will also be referred to as warm district heating with building cold production.
V. Cold combined heating and cooling configuration with cold network. This solution is based on the ultra-low configuration with cold network, in which the building/flat heat pump may also supply cooling. For simplicity, it will also be referred to as cold district heating and cooling.

2. Methods and data

This section provides an overview of the methodology applied to answer the two research questions. Due to space constraints, only an outline is included. The reader is referred to the Detailed Methodology in the supplementary material for a complete picture of the approaches taken in the research.

This study has circumscribed the research area to the economic aspect to address the two research questions. Although there exist other metrics such as the Simple Payback Time, Net Present Value, or Internal Rate of Return, the Levelized Cost of Energy metric is preferred as it allows a neat comparison to be drawn between technologies with very different lifespans and diverse capital and operational outlays.

The Levelized Cost of Energy (LCOE) is a widespread metric in energy sector analysis. It represents the cost of an energy unit, considering all the costs incurred during the commissioning, operation, and decommissioning of energy infrastructure [56]. It is the ratio between all the costs and energy flows in net present values. Unlike other authors [56–58], Monte Carlo simulations were only used in one case, and the values provided represent the mean LCOE estimate.

As the definition states, the estimation of the Levelized Cost of Energy, on the one hand, requires the assessment of the heat demands and, on the other hand, the determination of both the capital and operational expenditures for the different components of the various heating and cooling solutions. In detail, these costs comprise the capital investment and maintenance of the district heating networks, of heat production facilities (including thermal energy storages), of the connections to each consumer (i.e. substations), and the administrative costs borne by the district heating operator.

This section is divided into four subsections. The first includes an explanation of the technical characteristics of the different network configurations and other heating solutions. The second deals with the determination of the building heating and cooling demands. The third describes the various approaches for sizing the different components. The fourth addresses aspects of cost.

2.1. Description of district heating systems

The city of Bilbao is surrounded by several industrial facilities, which could supply abundant waste heat to the city [16]. However, the distance from the nearest plant (approximately 7 km) precludes its cost-effective exploitation until the supply area has reached a considerable size. Therefore, the estuary of the river Nervión, which crosses the city, will be used as the primary heat source for all network configurations. As illustrated in Fig. 3, water temperatures at the mouth of the estuary range from 12 °C to 21 °C, which makes it a suitable source for heat extraction.

For the warm network configurations (I, III, and IV), water from the river will be fed into a large heat pump, which will produce either heat or both heat and cold. On the contrary, for the cold configurations (II and V), there will be a simple thermal exchange with the network water, and the temperature boosting will be delivered by small heat pumps located in each building. In the case of the district heat pump, a gas boiler is also installed to cover the peak loads and act as a backup. A bio-oil boiler could easily substitute this gas boiler, were the gas grid to be totally phased out. The installation of gas boilers together with building heat pumps is not contemplated due to space constraints at the building premises. Furthermore, its inclusion would preclude a decommissioning of the natural gas distribution network.

The heat production units are also supported by Thermal Energy Storage (TES) in the form of district water tanks (buried in the case of the warm systems) and small units (installed at the buildings for the cold networks). Regarding the small tanks, a size upper bound of 5000 L is set, also motivated by space constraints at the building premises.

In the warm configurations, heat is distributed in a classic two-pipe network of pre-insulated bonded pipes, whereas cold is either transported in a parallel two-pipe network in configuration III or produced at the customers' premises through building chillers in configuration IV. In this latter case, these building chillers dispose of their waste heat into the heat network allowing other consumers to use it. Although using the return pipe as the heat sink would increase the building chillers efficiency, a return-to-supply connection is preferred as this avoids a reduction in the district-wide thermal storage capacity.

In the cold configuration, the water is circulated through a two-pipe uninsulated polyethylene (PE) network. For the sake of simplicity, it is assumed that all consumers deliver the same temperature drop when producing heat in configurations II and V and the same temperature rise when delivering cold in configuration V. In addition, no district-wide temperature boosting is installed, so the warm pipe is the same temperature as the river, and the cold pipe remains at a constant difference from the warm pipe. Furthermore, at the connection with the river the warm pipe is maintained at a higher pressure than the cold pipe as this would limit the installation of building pumping stations to the few buildings with cooling demand.

The warm networks are distinguished from the cold configurations in another respect. They are equipped with substations at the consumer premises, which serve as interfaces between the networks and the internal systems of the buildings, delivering space heating and cooling and preparing domestic hot water. In the cold networks, these apparatuses are not necessary as the building heat pumps play this role.

This description of the two main types of configurations enables a preliminary overview of their advantages and disadvantages. Concerning the distribution network, the cold configurations (II and V) only require a set of two uninsulated polyethylene pipes, whereas configurations I and IV require two insulated pipes, and configuration III requires four insulated pipes. Moreover, although cold networks will

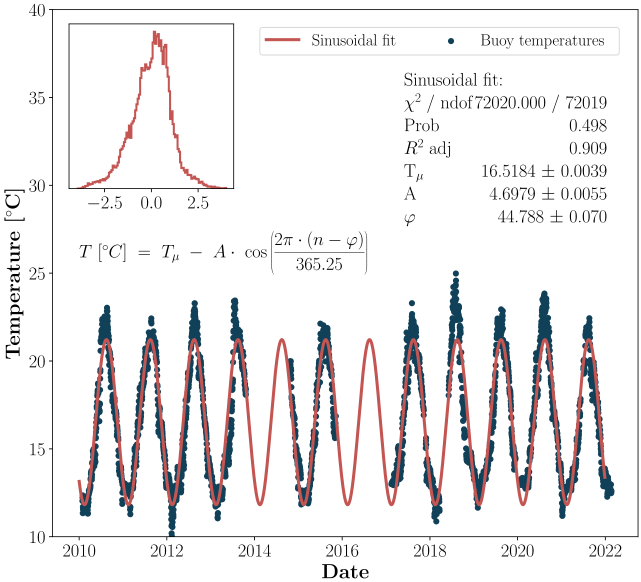

Fig. 3. Water temperatures in the Port of Bilbao. Source: Port of Bilbao [59].

typically necessitate higher flows due to lower temperature differences, differences in outer pipe diameter are unlikely to be significant due to the insulation thickness in pre-insulated pipes. These features will likely present a noteworthy benefit for cold networks; not only will capital costs be lower, but heat loss will also be negligible or even negative. On the contrary, pumping costs will be higher for cold networks, but these are usually neglectable when compared to heat production costs.[3] Therefore, pumping costs are disregarded in this study. Regarding heat and cold production, traditionally, heat production units had considerable economies of scale, but the current mass-production of small heat pumps may have eroded this advantage in warm configurations. However, warm systems may still enjoy other advantages in city-wide production, such as higher decoupling of heat production and heat use, thanks to larger storage sizes or higher flexibility for changing heat production over time. In this sense, there exists a lock-in effect with cold district heating in a similar fashion to heat pumps or gas boilers located at each consumer. Here, heat is produced at the consumer premises, and it is therefore more difficult to alter on a municipal scale. In addition, the operation and maintenance of an array of distributed heat pumps is bound to be more challenging and complex than one or a few production units. Finally, cold networks enable concurrent heating and cooling delivery with the same two-pipe network whereas warm district heating systems typically use a parallel district cooling network, whose cost can render the cooling supply unfeasible.

2.2. Heating and cooling demands

The methodology used was suitable for the intended comprehensive analysis of the energy attributes of urban structures within a city. Additionally, it facilitated the assessment of prospective decarbonization strategies for the city in question. This method was rooted in the concept of Building Stock Models (BSM), executed with the ENERKAD software [61–63], and enabled the computation of energy demands, energy consumption, and the associated environmental emissions for every building in the city on an hourly basis.

In this study, basic information from the cadastre [64] was used, including geometry, use, year of construction, and height of the building. This was complemented with information on equipment, heat source (e.g., natural gas, heating oil), and level of production (centralised at the building level or at each flat) obtained from various sources. In the case of public buildings, the municipality provided both the equipment and energy demand. For the remaining buildings, other sources such as energy certificates (e.g., Gangolells-Solanellas et al. [65]) and municipal registers or the regional registry were employed for high-capacity thermal installations (>70 kW) [66].

This information facilitated the calculation of building annual energy demand, as well as emissions and associated costs. Moreover, actual information on natural gas demand was obtained. This information was provided directly by the energy provider for various years by type of tariff [67] at census section level [68]. This information on actual energy use in relatively small areas[4] enabled refinements to the demand model to take into account the particular characteristics of each area, such as socio-economic aspects, empty homes, or renovations that had not been considered due to lack of information. It also facilitated the analysis of user behaviour, which can vary from one area to another depending on age or the number of people per dwelling. In this way, the performance gap typical of this type of model was largely avoided.

Once the demand data had been adjusted by zones and extrapolated to all buildings, a calibrated annual heating and cooling demand model was obtained for the whole city at the building level. Later, hourly space heating demand profiles were obtained with the degree day method. However, these profiles do not realistically represent the building energy use profiles. This is not only due to the physical characteristics of buildings but chiefly because of consumer behaviour (i.e., night setbacks). The district heating operator Giroa-Veolia [70] provided actual hourly profiles from a system located in the same region, from which hourly archetype profiles were created. These archetype profiles were then imposed over the degree-day profiles, rendering the final hourly profiles for each building.

Using this information, a heat demand density map was generated, grouping the demands of all the buildings contained in each grid for the whole city. This heat density map, together with other layers [71], were used to select an area of the town for the detailed analysis of the various decarbonization options. The primary criteria for this selection were heat density, the share of buildings with centralised heating systems, given that these are more easily connected to a district heating network, as well as distance to the river since a nearby location would facilitate the utilization of this heat source.

2.3. Sizing

The three following subsections present a brief description of the methods applied to size and estimate the total costs of all the elements of the various forms of heat and cold supply. The methods aim to minimize the Net Present Value of the total costs and, hence, the Levelized Cost of Energy. In the various calculations a discount rate of 3 % was applied.

2.3.1. Temperatures

A set of temperature assumptions were required for the sizing of the district heating network and the production units. A complete discussion of the rationale for these is provided in the Detailed Methodology, so this section presents them succinctly.

On the one hand, Table 1 presents the assumed required temperatures for space heating, domestic hot water, and space cooling at the consumer level. Generally, the temperatures were the same across the various configurations, and they only differed in the domestic hot water preparation. Here, the assumed return temperature in the warm networks was substantially higher than in the cold networks. The purpose of this conservative estimate was not to underestimate the flows when sizing the pipe network. In the cold networks (II and V) these temperatures were used to calculate the efficiency of the heat pumps.

On the other hand, Table 2 shows the temperatures in the district networks. In the warm networks (I, III and IV) the supply and return temperatures were assumed to be the same as the temperatures required for space heating (80 °C and 50 °C), disregarding the effects of the return flow from domestic hot water and summer bypasses. The district cooling network, present in configuration III, has system temperatures that are also equal to those assumed for space cooling in Table 1 (6 °C and 16 °C). Concerning the cold network (configurations II and V) the supply temperature was assumed to be the same as the river temperature and the return temperature was assumed to follow the supply temperature separated by a constant temperature difference (ΔT_{cold}). In configuration V, the heat pump's cold production was assumed to use the supply and return flows in reverse to achieve a better efficiency and, hence, the inverse temperatures.

2.3.2. Pipe network

The network was designed using a two-step heuristic approach. First, two proposals for the network topology were obtained by applying two routing algorithms. Second, the pipe diameters were sized to minimize cost while fulfilling hydraulic constraints. This method did not

[3] According to Frederiksen and Werner [60], head losses typically account for 1 % of the heat demand and they contribute to supply the heat demand.

[4] Census sections typically range from 1000 to 2500 inhabitants. Their cartography can be downloaded at the Instituto Nacional de Estadística website [69].

Table 1
Energy demand temperatures according to configuration.

	I	II	III	IV	V
Space Heating Supply Temperature	80°C	80°C	80°C	80°C	80°C
Domestic Hot Water Supply Temperature		60°C			60°C
Space Heating Return Temperature	50°C	60°C	50°C	50°C	60°C
Domestic Hot Water Return Temperature	40°C	10°C	40°C	40°C	10°C
Cold Supply temperature	–	–	6°C	6°C	6°C
Cold Return temperature	–		16°C	16°C	16°C

Table 2
Network temperatures according to configuration.

	I	II	III	IV	V
Heat Supply temperature	80°C	T_{river}	80°C	80°C	T_{river}
Heat Return temperature	50°C	T_{river} - ΔT_{cold}	50°C	50°C	T_{river} - ΔT_{cold}
Cold Supply temperature	–	–	6°C	50°C	T_{river} - ΔT_{cold}
Cold Return temperature	–	–	16°C	80°C	T_{river}
ΔT_{warm}	30°C	–	30°C	30°C	–
ΔT_{cold}	–	10°C	–	–	10°C
$\Delta T_{DistrictCooling}$	–	–	10°C	–	–

guarantee the minimum global cost but was likely to be capable of delivering an acceptable result.

The topology of the network was constructed on top of the road network retrieved from Open Street Maps [72]. With the aid of several R packages[5] [75–79], a pipe network was designed so as to minimize the length between each consumer and the production plant following Dijkstra's algorithm [80] or to minimize the total network length (the Steiner problem) solved using the methodology presented by Kou [81].

The pipe diameter sizing was calculated separately for each network type and followed the second method devised by Tol and Svendsen [82].

In the design load situation, the maximum load for space heating, domestic hot water, and space cooling was calculated differently depending on the network type.

For the warm configurations (I, III, and IV), the maximum load of each consumer was taken directly from the maximum hourly values provided by Enerkad. Furthermore, coincidence factors for domestic hot water demand were calculated after Holmberg [83] in each network stretch, whereas no simultaneity factor was assumed for either space heating or space cooling. Later, the heat losses derived from this sizing were used in the heat production optimization.

On the contrary, in the cold network configurations (II and IV), the required maximum load of low-grade heat was obtained after each building heat pump was optimised as described in the next section given that the low-temperature heat from each heat pump is not directly linked to the space heating and domestic hot water demands. Otherwise, additional assumptions should have been made concerning the design load from each building heat pump.

The supply and return temperatures followed those indicated in Table 2. In the warm network configurations, different return temperatures were assumed for space heating (50 °C) and domestic hot water (40 °C) which rendered different return temperatures depending on the proportion of these two heat uses.

Heat loss was calculated following the steady-state formulae of Wallentén [84] and the transient correction formula of Bøhm [85]. In these formulae, the ground temperatures were determined with data from NOAA [86] and fed into the equations of Heller [87].

The minimum pressure in the network and the pressure loss in the substations were set to 10 mH_2O and two maximum pressure levels were studied (60 and 100 mH_2O). The former would enable the use of cheaper substations with direct connections, which is widespread in Denmark.

2.3.3. Heat and cold production

Mathematical programming was utilized to determine the optimal combination of unit size and operation with the goal of minimising the combined capital and operating expenditures. A tailored model was developed for each configuration.

In the classic configuration with warm network (configuration I) the optimal sizing of the heat pump, accumulation tank, and the dispatch of the units was calculated using linear programming (LP) inspired by the formulation by Dorotić [88], although heat loss in the thermal energy storage was included in a similar fashion to Åberg et al. [89].

In the ultra-low configuration with cold network (configuration II) each building was analysed separately, unlike Wirtz [42], who simultaneously optimised all the buildings. Furthermore, since the necessary temperatures for space heating and domestic hot water production differ, it was assumed that the heat pump produces either space heating or domestic hot water at each respective temperature, possibly storing the output in separate thermal energy stores. This "either" constraint necessitated solving the dimensioning and dispatching problem through mixed integer linear programming (MILP). Heat losses in the thermal energy storages were disregarded to accelerate computations. The influence of this was assumed to be small as small water tanks typically experience one daily cycle.

In the warm combined heating and cooling configuration with warm network (configuration III), the heat pump may produce either heat and cold separately or simultaneously. The former achieves higher efficiencies due to the higher and lower heat source and sink temperatures, respectively, but the latter exploits the synergies of concurrent production. These different possibilities were implemented as MILP problems too.

In the classic configuration with warm network and building cold production (configuration IV), the heat pumps located at each building were independently optimised (LP), and the district's heat pump was operated with the building waste heat availability in mind (LP).

In the cold combined heating and cooling configuration with cold network (configuration V), the algorithm developed for configuration II was expanded to take the cold production possibilities into account in a way similar to configuration III.

In configurations I, III, and IV, the heat load at the city-wide production units results from the sum of the hourly values of the domestic hot water and space heating demands as well as the pipe network's transient heat losses. A similar approach applies to the city-wide cold load of configuration III. On the contrary, the loads in each building heat

[5] An R package is an extension of the programming language R consisting of a series of functions grouped in a standardised collection format to be distributed from a repository [73,74].

Table 3
Summary of technical and economic assumptions.

Unit	Investment Cost (I)	Efficiency	Lifetime	Energy Cost	Annual O&M
Centralised Substations	I [€] = 46.8 P [kW_{th}] + 13 100	100 %	25	–	140 €
Flat Substation and Connection	I [€] = 4000	100 %	25	–	50 €
Warm DH Network	I [€/m] = 4.314·DN + 354	–	25	–	1 % Investment
Cold DH Network	I [€/m] = 2.29·DN + 250	–	25	–	1 % Investment
City-Wide Thermal Storage (tank)	I [€/m^3] = 151·V[m^3] + 260 000	<100 %	25	–	–
City-Wide Thermal Storage (pit)	I [€/m^3] = 1922·D + 1724·D^2 + 41.06·H·D^2 + 3.389·H^2·D^2, H[m] & D[m]		25	–	–
City-Wide Heat Pump	I [€] = 2940 P_{el}[kW_{el}] + 410 000 I [€] = 703 P_{el}[kW_{th}] + 620 000	$\eta_{Lor.}$ = 50 %	25	Spot prices 2014–2019 & 6.3TD fees and charges	2 €/MWh_{th} & 2000 €/MW_{th} || 6000 €/MW_{el}
City-Wide Thermal Gas Boiler	I [€] = 60 P_{th} [kW_{th}]	100 %	25	100 €/MWh	1.1 €/MWh_{th} & 2000 €/MW_{th}
Building Storage	I [€/m^3] = 1830·V[m^3] + 2780	100 %	20	–	–
Building Water-to-Water Heat Pump	I [€] = 1325 P_{el}[kW_{el}] + 8300 I [€] = 377 P_{el}[kW_{th}] + 10 800	$\eta_{Lor.}$ = 40 %	20	Synthetic year based on spot prices 2014–2019 & 3.0TD fees and charges	2 €/MWh_{th} & 2000 €/MW_{th} || 6000 €/MW_{el}
Flat Water-to-Water Heat Pump	I [€] = 6000 (Heat Pump) I [€] = 2000 (Connection)	$\eta_{Lor.}$ = 40 %	16 HP 25 C.	Hourly PVPC 2014–2019	100 €
Building Air-to-Water Heat Pump	I [€] = 3490 P_{el}[kW_{el}] −1000 I [€] =1450 P_{el}[kW_{th}] + 5000	$\eta_{Lor.}$ = 40 %	20	Synthetic year based on spot prices 2014–2019 & 3.0TD fees and charges	2 €/MWh_{th} & 2000 €/MW_{th} || 6000 €/MW_{el}
Flat Air-to-Water Heat Pump	I [€] = 6000	$\eta_{Lor.}$ = 40 %	16	Hourly PVPC 2014–2019	100 €
Building Gas Boiler	I [€] = 10 064 (for 100 kW)	85 %	25	Eurostat (51 €/MWh)	956 €
Flat Gas Boiler	I [€] = 2000	85 %	20	TUR (80 €/MWh)	50 €

pump (in configurations II and V) are simply the hourly heat and cold demands of the buildings.

Concerning the heat pump's capacity to be optimised, two formulations were tested. One was based on the electric capacity inspired by EnergyPRO [90] and the other was based on the thermal capacity following Bach and Pieper [91,92]. In both formulations, the COP (coefficient of performance), which is the ratio between the thermal and electric capacities, was precalculated assuming a constant Lorenz efficiency [93,94]. Nevertheless, the COPs for cold production were determined using the model developed by Jensen [95]. For these COP-calculations, the temperature data presented in Table 1 were employed.

2.4. Data

2.4.1. Pipe network

For the warm networks, construction costs were taken from the sEEnergies project [96] and compared to data gathered from several district heating projects in the nearby region and the recently published comprehensive assessment [97]. No cost reduction was assumed for the combined installation of district heating and district cooling networks in parallel, albeit the 2020 national comprehensive assessment on district heating and cogeneration suggests a potential cost-saving of 33 % [97].

On the contrary, the cost of the cold networks, built on polyethylene pipes, was estimated based on a series of construction projects of potable water networks from the region of Madrid [98–111]. These prices were corrected to take into account the double pipe and the use of PE rather than cast iron.

2.4.2. Heat production

The various costs and technical features of large heat pumps were based on data gathered by Pieper [92] as well as the Danish Technology Catalogue [93]. The latter source was also employed to retrieve information on large gas boilers for district heating.

The Flexynets project [112], together with Gadd and Werner's data [113,114], were used to estimate the construction costs of large steel tanks. These costs were complemented with an appraisal on the cost of burying the water tank underground. This is elaborated from a study of the construction cost of a circular shaft for a metro station [115].

The capital costs of small water-source heat pumps for the cold networks were retrieved from the construction cost database maintained by CYPE [116], which also provided the costs of small water tanks and small natural gas boilers. On the contrary, information concerning air-source heat pumps was retrieved from a series of actual projects and budgets from several installers in Spain.

Energy Prices were retrieved from an array of sources. The Spanish transmission system operator provided electricity spot prices [117] and retail electricity prices [118] for the 2014–2022 period. Electricity network fees and charges[6] were obtained from the Spanish official gazette [119–121], and other supplementary electricity fees were found in other literature [122]. Natural gas prices for large domestic consumers were retrieved from Eurostat [123], whereas the regulated rate TUR [124–141] was used for flat gas boilers. All retail prices include all the costs borne by the consumer but exclude the Value Added Tax.

Electricity prices from a six-year period (2014–2020) were used for sizing the warm configurations (I, III, and IV), whereas the cold configurations (II and V) were optimised using a synthetic year built from the same data and with the methodology used for the meteorological Test Reference Year [142,143]. This was intended to reduce the computation time of the cold configurations.

2.4.3. Substations

The installation cost of building substations was assessed from a series of construction projects carried out in Spain. These costs were roughly 40 % higher than those provided by a manufacturer [144], costs in Italy [145], or Denmark [146]. Therefore, these were deemed conservative estimates as cost reductions should be achievable.

The connection costs of single flats to district heating were estimated using recent experience in the cities of Vienna [147] and Vitoria [148–152].

2.4.4. Administration

Beyond heat production, distribution, and connection expenses, the operation of a district heating systems also entails expenses for management and administrative personnel, software, consumer relations, and auditing, which can be summarised as administration outlays. These were established from data elaborated by the Danish District Heating Association [153]. Given that Spanish unit labour costs are half of those of Denmark [154], the value is bound to be rather conservative. These administrative costs were already included in the retail prices for

[6] These fees and charges depend on the voltage level. Building heat pumps bore the 3.0 TD tariff whereas the district ones used the 6.3 TD tariff. Further information on this is provided in the Detailed Methodology and the Supplementary Material.

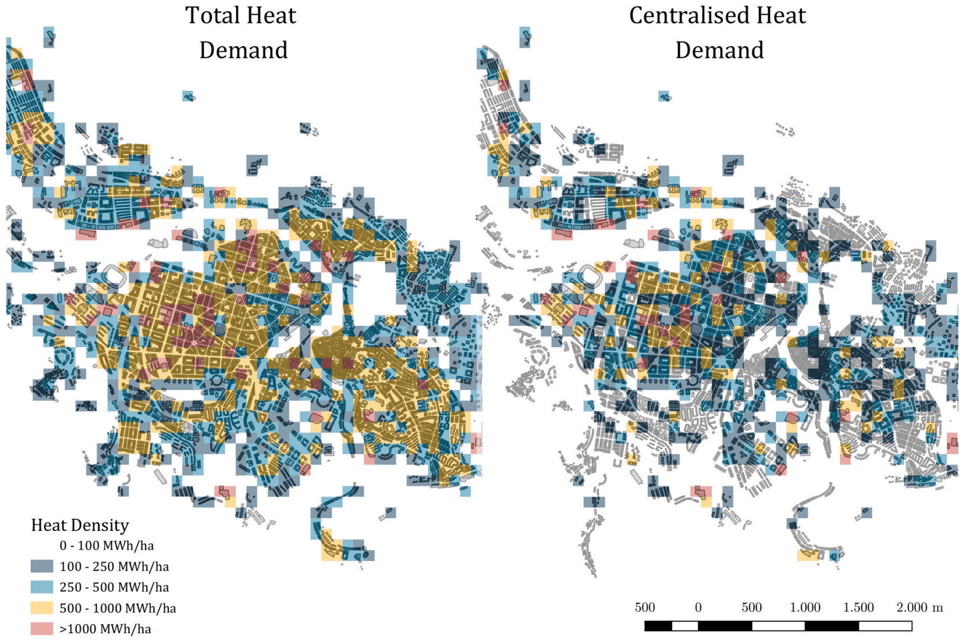

Fig. 4. Heat density map of the city of Bilbao.

electricity and natural gas.[7]

2.5. Overview of cost assumptions

A summary of the cost assumptions is shown in Table 3 and a full acount of these data is provided in the Detailed Methodology and the suplementary material.

3. Intermediate results

This section presents the results of the analysis carried out in Bilbao regarding area selection, network sizing and energy production optimization.

3.1. Heat demand mapping and area selection

The demand modelling generated a heat density map, which has been depicted in Fig. 4, wherein the left map represents the total heat demand, and the right map shows the heat demand in buildings with centralised heating systems. Approximately half of the heat demand occurs in buildings with centralised heating systems, as shown in Fig. 5, but Fig. 4 clearly illustrates that this distribution is not uniform. For instance, some areas, such as the Medieval Quarter, present high heat densities, but the demand is fulfilled at each flat.

The total heat demand of the municipality rises to 593 GWh; thereof 48 % stems from DHW and the remaining 52 % from space heating. This share is relatively constant throughout the city, but the system configuration, be it centralised or flat-based, and the energy sources vary significantly. Regarding the energy sources, electricity in the residential sector is more prevalent in low-income neighbourhoods, where it is used in the form of electric radiators and electric water tanks. In the service sector, air-source heat pumps predominate but, on the contrary, heat pumps are uncommon in the residential sector. Concerning fossil fuels, natural gas is used in both centralised and flat boilers, whereas heating oil is employed exclusively in buildings with centralised systems. Bottled gas has fallen to insignificant levels.

Given that buildings with centralised heating systems are more readily connected to a district heating network, the high centralised heat density area depicted in Fig. 6 was selected for this exhaustive analysis of district heating feasibility. This area's location, adjacent to the river, allows for an easy connection to this heat source. Furthermore, the entire Abando district was studied in the sensitivity analysis.

The in-depth area has a heat demand of 26 GWh (77 % centralised) and a cold demand of 3 GWh (only centralised), whereas Abando's reaches a heat demand of 130 GWh (55 % centralised) and 17 GWh of cold demand (only centralised). The in-depth area contains 176 buildings with annual heat demands ranging from 17 to 2200 MWh, a median centralised heat demand of 95 MWh, and average specific heat and cold demands of 44 kWh/m^2 and 15 kWh/m^2, respectively. The low specific heat demand is in line with the studies carried out by the IDAE [8,156] and other research on the city [157–159]. These results are likely the result of economic constraints rather than an energy-efficient building stock.

[7] For instance, in the regulated natural gas tariff (the TUR) the commercialization costs constitute 1.42 €/month and 0.83 €/MWh [155].

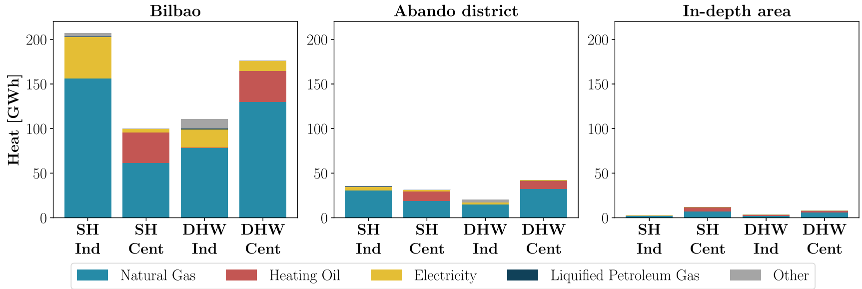

Fig. 5. Heat demand as a function of use (space heating (SH) or domestic hot water (DHW)), configuration (Flat or centralised (Cent), for the entire building) and energy source in the entire municipality of Bilbao, the Abando district, and the area.

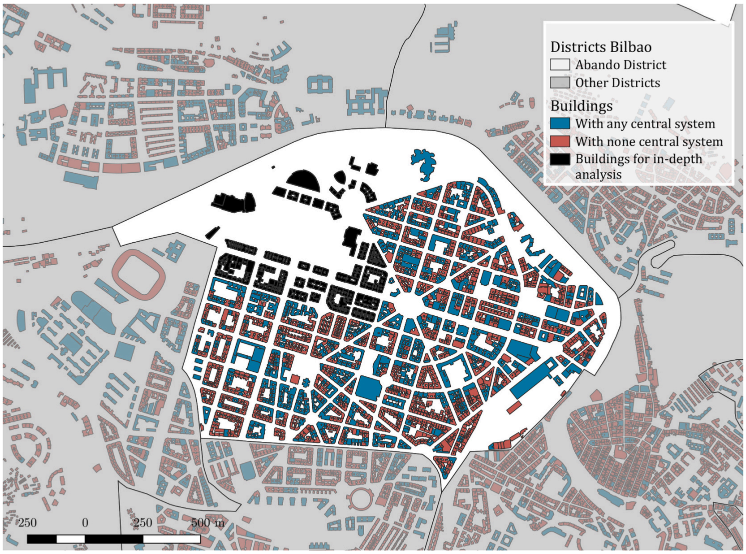

Fig. 6. Selected area and city districts.

3.2. Network

The upper part of Fig. 7 depicts the network topology (according to Dijkstra's algorithm) in configurations I and II along with the results from the pipe sizing, which are also shown in detail in Table 4. Both networks have a trench length of 12 396 m, leading to linear heat densities[8] of 1.62 and 2.1 MWh/m, for the centralised and total heat demand (space heating and domestic hot water). By comparison, the average linear heat density in all Danish systems has ranged from 0.86 to 1.01 MWh/m in the last decade [153,161–167]. Moreover, the figure shows that the cold network has larger diameters than the warm network.

The lower section of Fig. 7 shows two possible district cooling networks for configuration III (according to Dijkstra's and Kou's algorithms). In these cases, the linear cold densities are 0.76 and 1.15 MWh/m, respectively.

Concerning the topology of configurations I and II, as the figure shows, the network's length could be easily reduced by simplifying the paths through the central park. Although Kou's network was 22 % shorter, it entailed a higher cost as the average diameter nearly doubled (+90 %).

[8] The pipes in a network can be classified into service and distribution. The former connect each building to the distribution network [160], which forms the backbone of the grid. Sometimes linear heat densities are calculated using the length of distribution pipes. Bearing in mind that distribution pipes account for 72.4 % of the total trench length, the linear heat density would rise to 2.2 and 2.9 MWh/m, for the centralised and total heat demands, respectively.

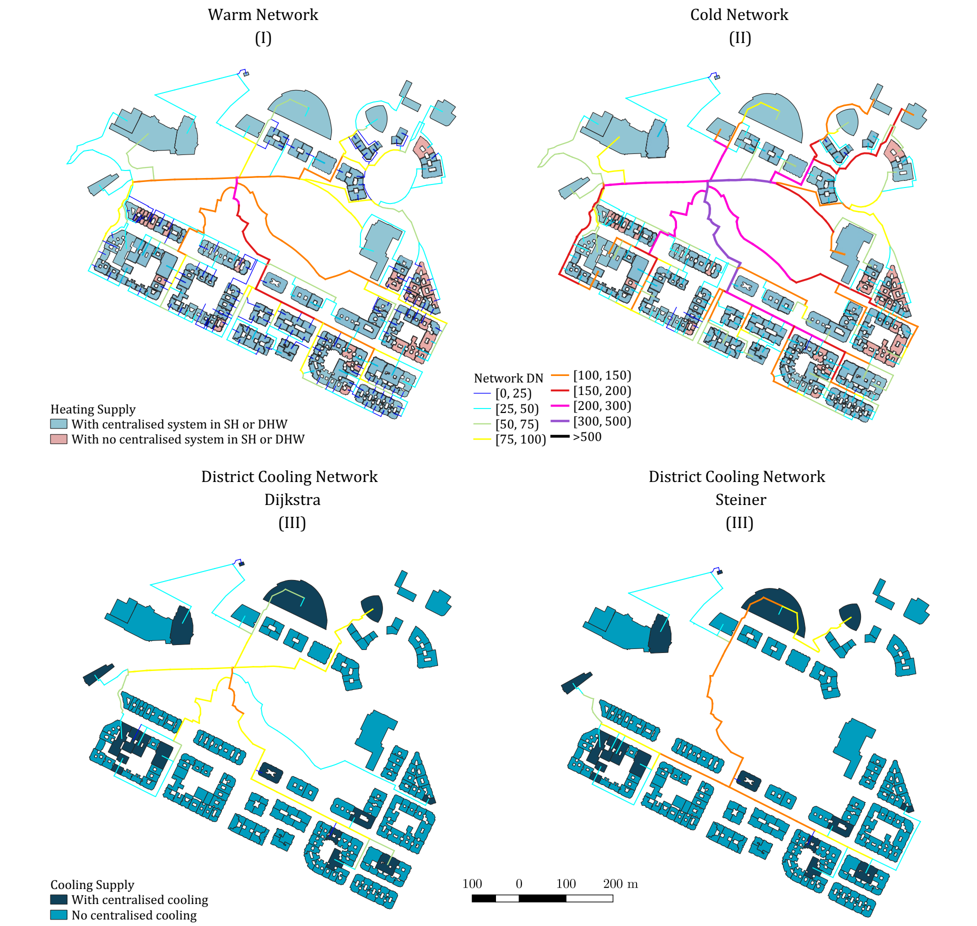

Fig. 7. Network topology and pipe sizes (DN) for configurations I and II (maximum pressure of 100 m of water column).

3.3. Heat production

Fig. 8 shows a sample of the heat load in configurations I and II. The uppermost figures depict the district heating load along with the heat pump, gas boiler production, and the thermal storage operation during three representative weeks. In this graph, the different modes of operation of the heat pump can be appreciated, from nearly continuous operation in the winter period to intermittent operation with long stops during the summer.

The intermediate and lowermost figures show the operation of a building heat pump in the cold district heating system, albeit, in this case, the domestic hot water and space heating production are plotted separately. As can be appreciated in the graphs, DHW and space heating production have distinct behaviours. Whereas for the former, the heat pump is typically actioned once a day (using the thermal storage to cover the daily demand), the heat pump is operated more continuously for the latter. This difference is likely explained by the higher COP of DHW production, which enables higher heat production.[9] Furthermore, during the summer, an apparent effect of neglecting the TES losses becomes visible; the space heating water tank remains loaded during the entire summer, which is an unrealistic situation.

In Fig. 9, the annual load curves for the warm and cold district heating solutions are plotted. Several observations can be drawn from this graph. First, the warm DH load is somewhat higher due to the higher heat loss in the warm network. Second, there exists a higher decoupling between the daily loads and heat productions in the warm network than in the cold network, due to the larger available storage size in the warm system (1815 m^3 vs 972 m^3). Third, the larger thermal storage, together

[9] This would not be the case, were the heat pump modelled with a *fixed* heat output rather than a *fixed* compressor capacity.

Table 4
District Heating network results (maximum pressure of 60/100 mH_2O).

	Trench Length (m)	Average Diameter (mm)	Heat Loss (MWh)	Investment (M€)
Classic Configuration with Warm Network (I)	Dist.: 8980 Serv.: 3416	77/68	1107/1034 5.5/5.1 %	8.2/7.7
Ultra-Low Configuration with Cold Network (II)	Distribution: 8980 Service: 3416	95/82	-1700/−1645 −8.5/−8.2 %	6.5/6.0
District Cooling Network (III) - Dijkstra	Distribution: 3438 Service: 510	83/73	−26/−26 −0.9 %	2.7/2.6
District Cooling Network (III) - Steiner	Distribution: 2606 Service: 510	99/86	−21/−21 −0.7 %	2.3/2.2

Length-Weighted Average Carrier Inner Diameter.

with the presence of the peak gas boiler, enables a reduction of the maximum heat pump load from 7.5 MW_{th} in configuration II to 5 MW_{th} in configuration I.

This decoupling can also be observed on an hourly basis in Fig. 10, where the frequency plots represent the heat load and the heat production that occurs in hours with specific electricity prices at the heat pump. Several observations can be drawn from this graph. First, even though the electricity spot prices for both configurations are the same, the electricity prices borne by the heat pumps differ due to different electricity grid fees, charges, and losses. Second, heat production tends to happen at lower electricity prices than the heat load, with reductions of 12.3 % for the Warm DH and 19.4 % for the Cold DH. Electricity prices in configuration II show more intra-daily variation than those in configuration I. Furthermore, the building heat pumps, and TES are capable of shifting production to the cheapest hours, typically at night. Hence, the price reduction for configuration II is higher than for configuration I, although the absolute values remain higher for configuration II as electricity prices in configuration II are consistently higher than for configuration I.

Table 5 summarises all the configuration results. On the one hand, the marginally dissimilar SCOP values for the district and building heat pumps stem from slightly different assumptions on Lorenz efficiency, source temperatures, and sink temperatures. Moreover, in configuration III, the concurrent heating and cooling production presents a lower COP than the sole cooling production, although this COP is nevertheless higher than if production took place separately. Additionally, the high COP of cooling production in configuration V is explained by the low temperature (~11 °C) of the cold network's return pipeline. On the other hand, the building TES of configurations II, IV, and V present a substantially higher number of loading cycles[10] than the district accumulator in configurations I, II, and III, which appear to act more as weekly storage than as daily storage.

Nevertheless, the most striking difference lies in the installed capacities for the heat pumps, which is markedly higher in the cold network solutions (II and V). The main cause of this contrast is the limited available storage at each building, followed by the slightly lower COP of the heat pumps, the presence of a peak gas boiler in the warm configurations, and the demand diversity in the district-wide production. For instance, the demand diversity entails a drop in the maximum hourly heat load from 24.9 MW_{th} to 23 MW_{th} in configurations I, III and IV., and the installation of a gas boiler enables, ceteris paribus, the reduction of the heat pump's installed capacity from 4133 MW_{el} to 1637 MW_{el} in configuration I.

4. Final results

This section deals with the results on levelized cost of energy and it follows with a sensitivity analysis of different aspects, such as energy prices, system size, and discount rate.

10 Calculated in accordance with Marguerite et al. [168].

4.1. Levelized cost of heat

The results of the LCOH analysis for configurations I and II are shown in Fig. 11, alongside two other forms of heat production: air-to-water heat pumps and natural gas boilers. Moreover, costs are provided for buildings with centralised systems (Building) and buildings with flat-based systems. In addition, the detailed figures underpinning the chart are presented in Table 6

The additional supply of cooling in configuration I renders configurations III, and IV. Similarly, the supply of cooling along with heating in configuration II leads to configuration V. In this sense, the impact of cold delivery may be assessed by calculating the marginal levelized cost of cold supply (i.e., the specific additional expenditures with respect to those that need to be incurred for supplying heat in configurations I and II). These marginal costs are gathered in Fig. 12.b where they can be directly compared to the levelized costs of heat for buildings (shown in Fig. 12.a).

In configurations III, IV, and V, no flat-based system was considered, as the cooling demand almost exclusively stems from service sector premises.

4.2. District heating feasibility

As illustrated in Fig. 11, in the current framework, none of the low carbon solutions (be they district heating or air heat pumps) would deliver cheaper heat than natural gas, especially if investment costs for the gas boiler are considered sunk costs and hence disregarded.

However, when considering low-carbon options, any district heating system would likely be cheaper than the air-to-water heat pumps. This uncertainty stems from the tiny sample size of air-source heat pumps, which caused broad confidence intervals in the coefficients of the investment cost curve. Monte Carlo simulations indicate that the total investment in air-source heat pumps could range from 18 to 28 million euros (1 σ), and there is a 1 % or a 12 % chance that air-source heat pumps would be a cheaper solution than warm and cold district heating, respectively.

4.3. Network comparison

4.3.1. Heating supply

Fig. 11 enables a comparison between the two district heating options for heat supply (configurations I and II). In this case, the warm classic configuration with warm network (I) would deliver a slightly lower cost to the consumers (90 €/MWh) than the ultra-low configuration with cold network (II), whose cost would rise to 108 €/MWh.

Despite the higher cost of the pipe network (23.5 €/MWh vs. 17.2 €/MWh), the warm system presents lower investment and running costs for energy supply, which leads to an overall lower LCOH. The higher investments for heat production in the cold network are explained, on the one hand, by a much higher installed heat pump capacity (5.8 MW_{el} vs 1.6 MW_{el}), which is not compensated by the lower specific investment cost of small heat pumps (1538 €/kW_{el} vs 3190 €/kW_{el}). On the other

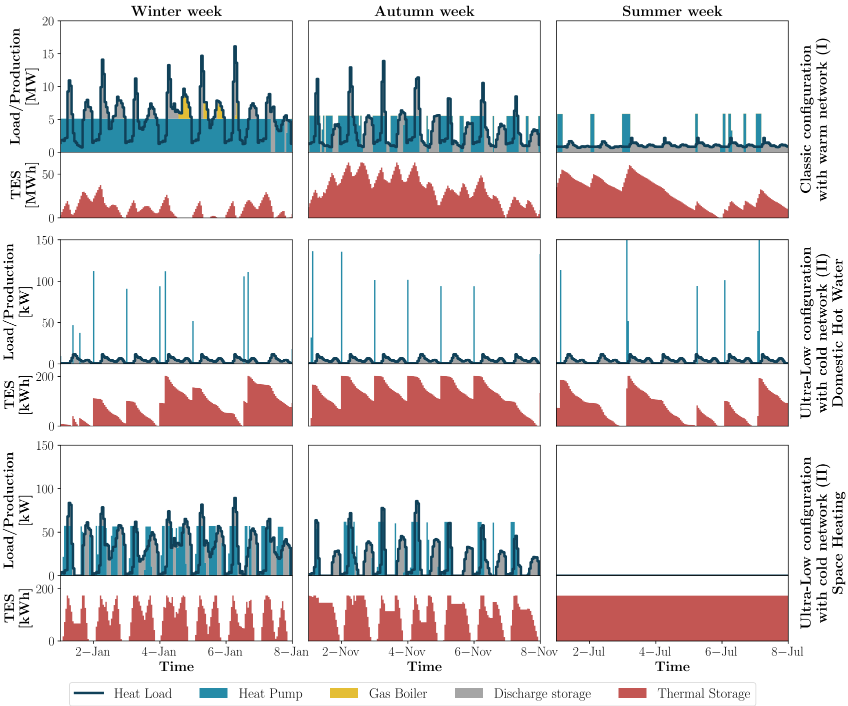

Fig. 8. Heat production and heat loads in the entire system in configuration I and in the median building in configuration II.

hand, it is explained by the economies of scale of large heat stores, which render these much more economical (553 €/m^3 vs 2613 €/m^3). The higher running costs in cold networks account for higher electricity prices and a reduced possibility of decoupling heat production and use due to the lower available heat storage. These are not offset by a higher COP in DHW production.

Warm and cold networks present another significant difference. Whereas the total LCOH in the warm system is nearly identical for every building (given that the different substation cost is a minor component of the LCOH), the total cost of supply for the cold system can vary widely. In Fig. 13 it has been plotted the levelized cost of heat related to heat production for each building. It is clear that even though most buildings present levelized costs below 100 €/MWh, and a few buildings with large heat demands have production costs below 50 €/MWh, there are a few buildings with extremely high production costs of up to 350 €/MWh. In these buildings, high peak demands and constrained storage push up the required heat pump capacities and, hence, the investment and LCOH.

4.3.2. Combined heating and cooling supply

As shown in Fig. 12, the warm district heating with city-wide cooling production (III) would not necessitate additional investments for cold production, and the marginal energy cost of the cold output would be negligible. However, the cost of district cooling substations would not be negligible, and the cost of constructing a district cooling network would be substantial. The lower linear cold density and the lower temperature difference explain this high network cost compared to the district heating networks. The total marginal cost of cold for this alternative would rise to 90.8 €/MWh.

The cost of the classic configuration with warm network and building cold production (IV) would be even higher, reaching 135 €/MWh. On the one hand, additional building heat pumps would need to be installed which would also be characterised by a low number of utilization hours. On the other hand, the production cost on the building level is relatively high, and reductions in heat production by the district heat pump would not compensate for these costs sufficiently.

In configuration V, the marginal cost would be negligible, at 13.4 €/MWh. No significant additional investments would be necessary, and the extra electricity cost would be minimal due to the low temperatures of the cold network.

Bearing in mind that the heat and cold demands account for 20 117 MWh and 2998 MWh, respectively, Fig. 12.c shows the weighted Levelized Cost of Energy.[11] Despite the much higher marginal LCOC for configuration III, its total LCOE is slightly lower (89.6 €/MWh) than configuration V's LCOE (96.6 €/MWh). Configuration IV's LCOE would be somewhat higher, reaching a value of 97.1 €/MWh. Despite the radically different marginal cooling costs, the levelized cost of both

[11] The weighted Levelized Cost of Energy is the mean of the Levelized Cost of Heat and the marginal Levelized Cost of Cooling, bearing in mind the different amounts of energy supplied.

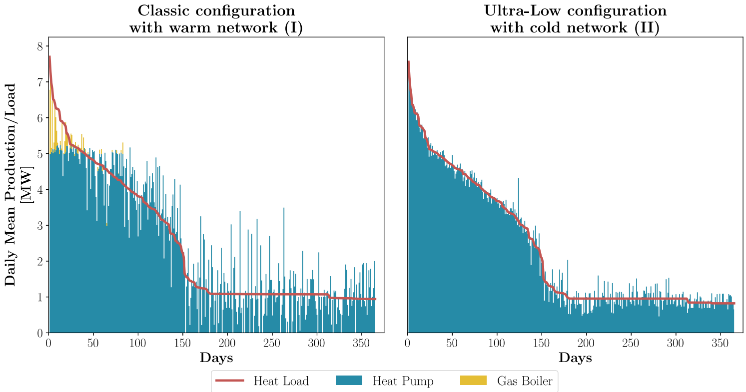

Fig. 9. Daily average district heating load and production for an entire year for configurations I and II.

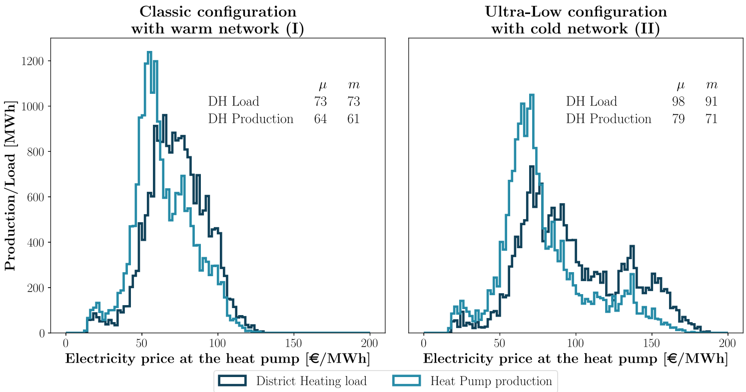

Fig. 10. Warm (I), and Cold (II), District Heating loads and heat pump production at different electricity prices.
The configuration I chart shows the dispatch results using the 1-year synthetic electricity prices with the unit capacities from the six-year optimization period.

heating and cooling would not differ significantly as the cooling demand is substantially lower than the heat demand.

4.4. Sensitivity analyses

The goal of this section is to explore the impact of several factors on the LCOE values of the various heating solutions.

4.4.1. Impact of carbon taxation on the Levelized cost of heat

As highlighted in the prior section, none of the low-carbon solutions would be cost-competitive in the current framework conditions. However, this situation could be reversed on condition that taxation on natural gas is raised, either through an increment of the energy tax (currently at 0.65[12] €/GJ [169,170]) or if the ETS2 for buildings and transport is implemented [171]. For example, Fig. 11 highlights the impact of a carbon price of 100 €/ton, which is at the lower end of recent estimates for the social cost of carbon [172,173]. However, a price of 48 €/ton and 19 €/ton would suffice to make warm district heating economically cost-effective in buildings with centralised and flat systems, respectively.

4.4.2. Impact of the energy crisis on the Levelized cost of heat

The energy crisis triggered by the Russian invasion of Ukraine caused a drastic increase in energy prices. Gas prices in the European market rose nearly ten times,[13] quadrupling electricity prices [117]. This increase in electricity spot prices has been somewhat lower than in other European countries due to the introduction of the Iberian Exception in June of 2022 [175].

As shown in Fig. 14, these price increases would drag up the LCOH

[12] Energy tax excluding VAT.

[13] The volume-weighted annual average price in the Dutch TTF increased from 15.3 €/MWh to 153.2 €/MWh between 2019 and 2022 [174].

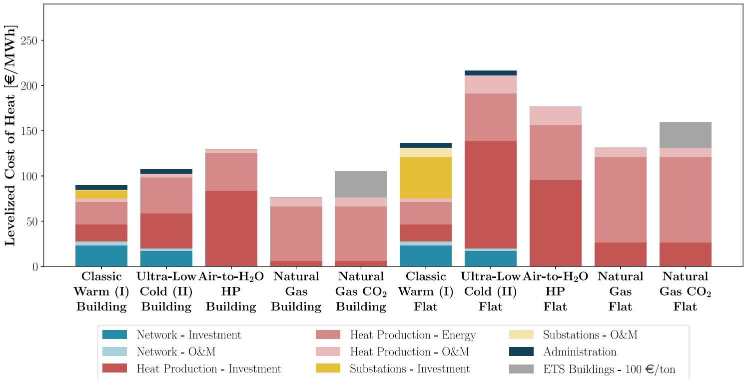

Fig. 11. LCOH comparison between the two district solutions (I & II), air-to-water heat pumps, and natural gas boilers.

Table 5
Optimization results for warm, (I, III, and IV) and cold, (II, and V), district heating.

		Classic with warm network (I)	Ultra-Low with cold network (II)	Warm Combined H&C with warm network (III)	Classic with warm network and building cold production (IV)	Cold Combined H&C with cold network (V)
District Heat Pump	MW_{el}	1.637	–	1.637	1.636	–
Building Heat Pump	MW_{el}	–	5.812	–	1.55	5.834
Gas Boiler	MW_{th}	7.7	–	7.7	7.7	–
Thermal Storage Heat	MWh m^3	63.2 1815	41 972	62.9 1805	63.1 1810	41 971
Thermal Storage Cold	MWh m^3	–	–	0 0	0.9 81	0 0
Number of Cycles of TES	–	164	DHW: 445 SH: 308	Heat: 153 Cold: 0	Heat: 149 Cold: 443	DHW: 415 SH: 299
HP Heat Production	MWh	20 971	20 116	River: 18 053 Combined: 2954	19 162	Network: 20 116 Combined: 0
HP Cold Production	MWh	–	–	River: 985 Combined: 2013	2998	Network: 2998 Combined: 0
SCOP	–	3.22	SH: 2.39 DHW: 5.39 Total: 3.08	Heat River: 3.17 Cold River: 5.43 Combined: 5.28	Heat River: 3.19 Combined: 2.42	SH: 2.39 DHW: 5.39 Cold: 17.28
Gas Boiler Production	MWh -	348	–	353	352	–

for the various heating solutions without changing their relative circumstances. Despite the soaring gas prices in the international spot markets, natural gas remains the cheapest heating solution for several reasons. On the one hand, the central government kept retail prices below the market. Firstly, price increases for small consumers[14] were capped at 15 % per quarter in 2021 [176], and later, the resulting deficit was covered by general tax revenue [177]. Moreover, a new regulated tariff was introduced for centralised systems [178]. On the other hand, gas companies secured lower prices through long-term agreements, as evidenced by the significant gap between average import prices (81 €/MWh and 52 €/MWh for liquefied and gaseous natural gas [179]) and average spot prices (153 €/MWh for the TTF).

4.4.3. Impact of thermal storage size and electricity fees on Cold District heating

The thermal storage capacity for cold district heating was limited to two tanks of 5000 L each per building due to space limitations. Were this limitation to disappear, heat production could be decoupled from heat demand to a much greater extent, taking advantage of low electricity prices. As shown in Fig. 15.a, if other costs are disregarded, the LCOH of heat production would drop by 14.1 €/MWh from 80.5 €/MWh to 66.4 /MWh (option B). This reduction is explained by an increase in the storage volume from 972 m^3 to 1681 m^3 and the subsequent decrease in the heat pump's installed capacity from 5812 kW_{el} to 3077 kW_{el}. In addition, this change would also remove buildings with a very high LCOH (depicted in Fig. 15.b) and would result in the cold network delivering heat at a cost nearly on par with the warm system.

In the hypothetical (and unrealistic) case that buildings also had access to the same electricity grid conditions as the centralised heat pumps (option C), it would be possible to further reduce the LCOH by 9 % (to 59.6 €/MWh). This illustrates that electricity fees and grid losses influence end heat costs significantly.

4.4.4. Impact of discount rate

All the Levelized Cost calculations were performed under the assumption of a 3 % discount rate. Although this discount rate may be sensible from a public perspective, a private investor will likely demand

[14] Consumers with a demand below 50 MWh/year.

Table 6
Detailed LCOH decomposition for alternative solutions.

		Network		Production			Substations		Administration	Total
		Investment	O&M	Investment	Energy	O&M	Investment	O&M		
		(€/MWh)	(€/MWh)	(€/MWh)	(€/MWh)	(€/MWh)	(€/MWh)	(€/MWh)	(€/MWh)	(€/MWh)
Classic with Warm Network (I)	Building	23.5	4.1	19.1	25.1	3.3	8.8	1.0	5.0	89.9
	Flat	23.5	4.1	19.1	25.1	3.3	45.9	10.0	5.0	136.0
Ultra-Low with Cold Network (II)	Building	17.2	3.0	38.4	39.9	3.7	0.0	0.0	5.0	107.3
	Flat	17.2	3.0	118.5[1]	52.8	10.1	0.0	0.0	5.0	216.5
Warm Combined H&C with Warm Network (III)	Building	27.2	4.7	16.6	23.3	2.6	9.2	1.0	5.0	89.6
Classic with Warm Network and Building Cold Production (IV)	Building	20.4	3.6	23.6	31.7	2.6	7.6	0.9	5.0	95.3
Cold Combined H&C with Cold Network (V)	Building	17.2	3.0	31.7	35.7	2.2	0.0	0.0	5.0	96.6
Air-to-Water Heat Pumps	Building	0.0	0.0	83.4	42.2	3.9	0.0	0.0	0.0	129.5
	Flat	0.0	0.0	95.5	61.0	20.0	0.0	0.0	0.0	176.5
Natural Gas	Building	0.0	0.0	6.1	60.6	10.1	0.0	0.0	0.0	76.7
	Flat	0.0	0.0	26.9	94.2	10.0	0.0	0.0	0.0	131.0

[1]This figure includes both the cost of the flat water-to-water heat pump and pipe connection from the network to the flat.

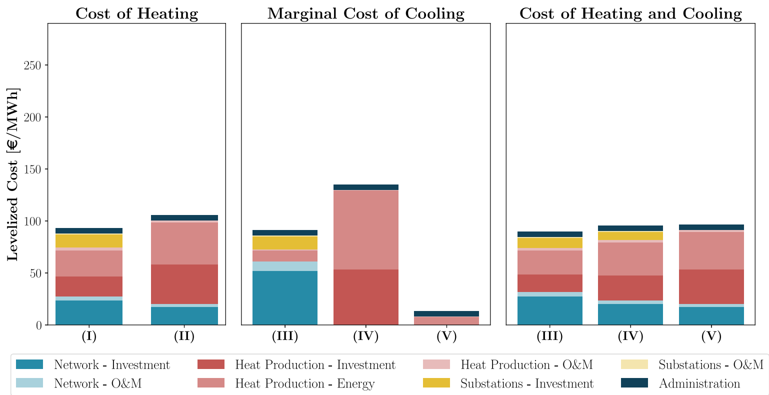

Fig. 12. LCOH of configurations I and II, marginal LCOC, and total LCOE for configurations III, IV, and V in buildings.

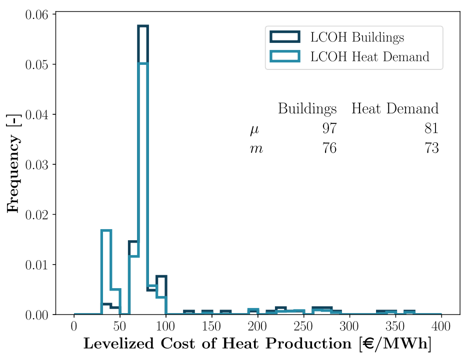

Fig. 13. Levelized cost of heat production in the ultra-low configuration with cold network (II).

a higher return. Fig. 16 depicts the levelized cost of heat under a 9 % discount rate. The cold DH (II) remains the most expensive option in this scenario, albeit it is less sensitive to a higher discount rate than the warm DH solution (I). The former's LCOH increases by 34% to 144 €/MWh compared to 43% for the latter, whose total LCOH rises to 130 €/MWh.

In both cases, the installed capacities change very little, and the slightly smaller investments do not compensate for the higher capital costs.

4.4.5. *Impact of district heating system expansion*

Expanding the district heating network to the entire district of Abando would enable the supply of 73 GWh of heat to buildings with centralised heating systems. Alternatively, it could supply 130 GWh were all the consumers connected to the network. This neighbourhood expansion would involve a large increase in the network length from 12 to 49 km (or 69 km for all buildings), which would render a slight reduction in the linear heat density from 0.74 MWh/m to 0.6 €/MWh. This reduction would bring the network cost up to 28 €/MWh, which would be partially compensated for by a 4.4 €/MWh drop in heat production costs due to economies of scale. Given the slight increase in

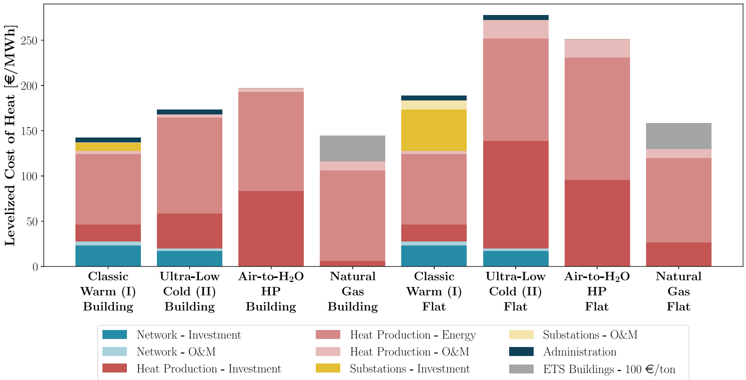

Fig. 14. LOCH comparison during the energy crisis.

substations costs, the LCOH would rise from 90 €/MWh to 94 €/MWh (as illustrated in Fig. 16).

Furthermore, the increase in the heat demand would allow a cost-effective heat transport from two nearby facilities, either the incineration plant of Zabalgarbi or the cement factory of Rezola-Arrigorriaga. Assuming a marginal cost of the waste heat of 15 €/MWh, the total LCOH for the warm DH solution would fall to 84 €/MWh since the specific cost of heat transport would barely reach 9 €/MWh. The waste heat price ought to be lower than 20–25 €/MWh for this solution to be competitive.

5. Discussion

5.1. District heating feasibility

The district approaches are able to deliver the cheapest low-carbon heating and cooling in the base case and during the energy crisis. In addition, warm district heating is competitive even if a high internal rate of return is required, and if the system reaches a certain size, it can exploit industrial waste heat cost-effectively. Building or flat heat pumps not only present higher capital costs but also generate higher operating expenditures due to higher consumer electricity prices and lower efficiency.

Unfortunately, for decarbonisation under the current framework conditions, none of the low-carbon solutions would be economically viable by comparison to the main form of heat supply, natural gas. The negligible energy taxation in the country[15] of 2.7 €/MWh compared to 28–42 €/MWh in Scandinavia and the lack of carbon pricing that could internalise the social cost of carbon make this solution the cheapest alternative. Tackling this challenge would require a combination of subsidies to low-carbon technologies, such as the French *Fonds Chaleur* [180,181] or increased taxation on fossil fuels. Increased taxation could be combined with a rebate (such as the Canadian carbon tax [182]) in order to address its regressive consequences.

In summary, the results of this case study highlight how district heating can be a cost-competitive option in a dense urban environment with a mild Southern European climate. However, this would only occur once the present and future costs for climate change are internalised, and the private and social economies are aligned. This feasibility defies the conventional wisdom that district energy systems are only adequate solutions in cold northern climates and confirms prior research carried out on the continental scale [14].

5.2. Network comparison

As illustrated in section 3.2, the ultra-low temperature configuration with cold network (II) leads to a lower network cost than the classic configuration with warm network (I), due to its lower construction costs. On a broader perspective, beyond this case study, this result is likely to be valid in most circumstances unless very high temperature differences are achieved in the classic configuration (I) or if there are minimal economic savings when uninsulated pipes are used [183]. Furthermore, the ultra-low temperature configuration (II) is bound to be more advantageous in sparse areas as the classic configuration's specific heat losses are much higher in these areas [184] but these heat losses will remain negligible for the ultra-low configuration.

However, when all heat supply costs are taken into consideration, the economic benefit of city-wide heat production more than compensates for the higher network cost. This causes the warm network (I) to deliver cheaper heat.

On the contrary, once the cooling demand is taken into account, this cost difference nearly vanishes, and both district solutions (the warm combined heating and cooling configuration with warm network (III) and the cold combined heating and cooling configuration with cold network (V)) would lead to similar energy costs. This is because the district cooling network costs in configuration III are relatively high due to the low linear cold density and a low temperature difference.

Nonetheless, the results should be analysed in a context-dependent manner. In the case in question, as well as in the densest urban areas, the network cost accounts for a small fraction of the total system cost, and the lower heat production cost of warm DH compensates for its higher piping outlays. In sparser areas, the network cost [185] and heat loss [184] may rise to the point where warm DH may be unfeasible, while a cold network may still be an economically sound solution given its lower piping expenses and null heat loss. In very sparse areas, individual heating solutions (such as heat pumps) would likely be advantageous as their cost is "*not*" sensitive to heat density.[16] Similarly, the warm combined heating and cooling configuration with warm network (III) is likely to deliver a more competitive service in those areas with a

[15] Energy tax excluding VAT.

[16] Electricity grid costs are likely correlated to urban density, but electric tariffs do not reflect this.

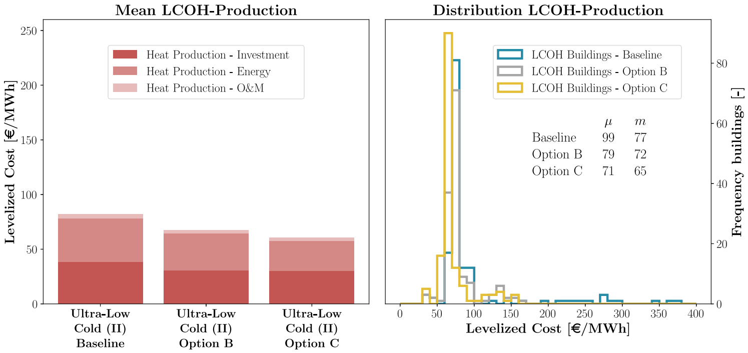

Fig. 15. Mean and frequency distribution of heat production LCOH for variations of configuration II in buildings.

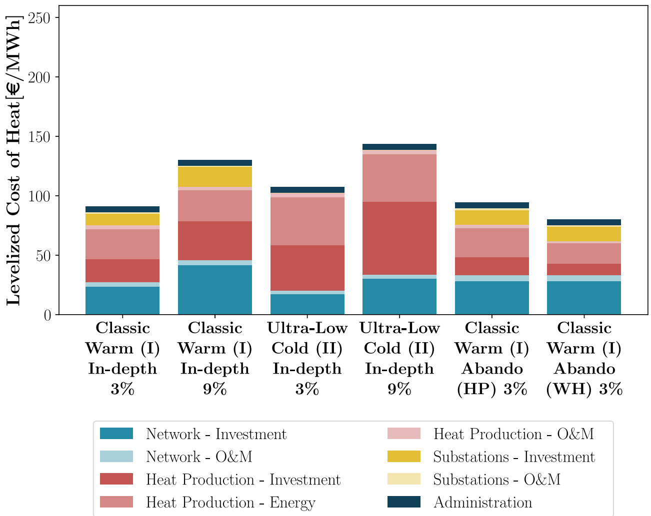

Fig. 16. LCOH for configurations I and II, in the in-depth area under two interest rates, and configuration I in the entire Abando district depending on the form of supply (heat pump (HP), or waste heat (WH)) for building solutions.

high linear cold density and, hence, low network cost. By contrast, cold district heating would be economically beneficial in areas where the linear cold density were too low.

The warm district heating options I, III, and IV would also be supported by other advantages not considered in this study. These include the improvement of structural energy efficiency when exploiting industrial waste heat, securing industrial employment through increased revenue streams, and short and long-term energy flexibility. The short-term flexibility is exemplified in the production curves of this case study, where there is a higher production variation of the warm system in response to electricity prices. A real example of this flexibility is also delivered by district heating in Denmark. Here, DH-based power-to-heat technologies already contribute to a better use of variable renewable energy sources [186] and the energy mix has significantly changed during the last decades [187].

Conversely, a cold network (either the Ultra-Low configuration with cold network (II) or the Cold Combined Heating and Cooling configuration with cold network (V)) could prove to be advantageous in a more realistic progressive network expansion, a situation which has not been explored in this study. In this scenario, the construction of the network and the connection of consumers would take place steadily over the years rather than all at once at the beginning of the project. In these circumstances, the deferral of heat production investments could lead to a lower net present value and, hence, a lower levelized cost of heat. This situation is more likely to arise in new areas under development (where new buildings are gradually erected) or in an existing neighbourhood (when a high connection may not be rapidly achieved).

On the other hand, it is likely that the costs of warm (I, III, and IV) and cold district heating (II and V) have been over and underestimated, respectively. This would have tilted the economic balance towards cold networks (II and V) slightly. First, the costs of the small water-to-water heat pumps are substantially lower than the costs of utility-scale heat pumps. It may be possible that heat pumps do not present clear economies of scale (as is the case for natural gas boilers) or it could be that the differences in labour costs between Spain and Denmark are higher than the economies of scale, leading to small water-to-water heat pumps (based on Spanish data) having lower unit costs than district heating heat pumps (based on Danish data). Second, the small heat pump installation costs that can be deduced from CYPE's database are lower than the installation costs of district heating substations from actual projects despite substations being simpler apparatuses, and the total costs of substations are substantially higher than the data provided by industrial companies. Third, the costs for conventional steel DH pipes have likely been overestimated as similar projects in a nearby region have been more economical.

6. Conclusions

This study has aimed to answer two research questions: whether district heating is economically viable and how district heating solutions compare to each other and other heating alternatives economically. A comprehensive analysis of the levelized cost of energy in an area of the city of Bilbao, Spain reaped the answers to these questions.

Concerning the first research question, district heating solutions are economically viable in a high-density urban environment characterised by a mild climate when compared to individual heat pumps. However, they are not able to outcompete the incumbent heating solution (natural gas) in the current framework conditions since the current taxation on natural gas does not internalise the social cost of carbon.

Regarding the second research question, the classic configuration with warm network (I) leads to lower costs than the ultra-low temperature configuration with cold network (II). This is not only true in the base case but also with high electricity prices, a high discount rate, and especially if the system is expanded so that industrial waste heat can be exploited cost-effectively. However, if the system were also to deliver cooling, the warm combined heating and cooling configuration with warm network (III) and the cold combined heating and cooling configuration with cold network (V) would have similar energy costs, albeit these costs would be slightly lower for the former.

CRediT authorship contribution statement

Luis Sánchez-García: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Helge Averfalk:** Writing – review & editing, Validation, Supervision. **Nekane Hermoso-Martínez:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Patxi Hernández-Iñarra:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Erik Möllerström:** Writing – review & editing, Supervision, Funding acquisition. **Urban Persson:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data as well as additional methods are made available in the supplementary material

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124384.

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Chapter 9

Appendix

Paper IV Detailed Methodology

Detailed Methodology

Luis Sánchez-García[a*], Helge Averfalk[a], Nekane Hermoso-Martínez[b], Patxi Hernández-Iñarra[b], Erik Möllerström[a], Urban Persson[a]

[a]School of Business, Innovation and Sustainability, Halmstad University, PO BOX 823, SE 30118 Halmstad, Sweden

[b]TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, 48160 Derio, Spain

* Corresponding author: luis.sanchez_garcia@hh.se

1 Introduction

This document delves into the various approaches used to estimate the cost of the different energy sources. It consists of two parts, the first one dealing with the methodology, and the second addressing the required data. Both sections cover the cost of energy conversion, distribution, and use by the final consumer.

2 Levelized Cost of Energy

The economics of the various heating solutions were studied by means of the levelized cost of energy (LCOE), heat (LCOH), and cold (LCOC). The levelized cost is a widespread metric in the energy sector that represents the cost of an energy unit, taking into account all the costs incurred during the commissioning, operation, and decommissioning of an energy infrastructure (Aldersey-Williams & Rubert, 2019). It is the ratio between the Net Present Value (NPV) of the costs, and the NPV of the supplied energy as shown in Equation (1). Should the energy sales be constant over the entire lifespan of the infrastructure, as in this study, the prior ratio simplifies into Equation (2).

$$LCOE = \frac{\sum_{y=1}^{n} \frac{I_y + C_{E_y} + O\&M_y + A_y}{(1+r)^y}}{\sum_{y=1}^{n} \frac{E_y}{(1+r)^y}} \quad (1)$$

$$LCOE = \frac{a \cdot I + C_E + O\&M + A}{E} \quad (2)$$

$$a = \left(\frac{r \cdot (1+r)^n}{(1+r)^n - 1}\right) \quad (3)$$

Where:

- E is the annual energy delivered.
- I_y is the investment carried out in year y.
- C_{E_y} is the energy cost in year y.
- $O\&M_y$ is the operation, and maintenance cost in year y.
- A_y is the administration cost in year y.
- a is the annuity ratio; this is, the fraction of the initial investment that needs to be repaid every year taking into account the interest rate. It is calculated according to Equation (3).
- r is the discount rate in real terms. Generally, 3% in this study.

Given that it is impossible to know with absolute certainty the values for the different outlays, and the evolution of the heat demand over time, the Levelized Cost of Energy ought to be calculated as a probability distribution by means of Monte Carlo simulations in a similar fashion to that presented by (Aldersey-Williams & Rubert, 2019) for various electricity generation units, (Saini et al., 2023) for a cold district heating system or (Marx et al., 2023) for a regional district heating transmission network.

Nevertheless, due to time constraints, Monte Carlo simulations were not generally used. Solely in one case, building air-to-water heat pumps, this method was applied so as to assess the potential variability in capital expenditures due to the high uncertainty in the cost function. A detailed description is included in the supplementary material.

3 Loads

This section deals with the determination of the loads employed for sizing both the network as well as the heat production units. Even though this section could be integrated within sections 6. Distribution and 7. Production, it has been preferred to present these values in their own section.

3.1 Network

This subsection describes the loads used at each consumer in order to size the pipe network and obtain each pipe diameter. The main differences between configurations I and II lies in the fact that the loads in configuration I were mostly directly derived from the heat demands whereas in configuration II stemmed from the heat production unit sizing carried out in each building.

3.1.1 Classic configuration with warm network

The design space heating demand for each building was directly extracted from the dataset elaborated by Tecnalia as the maximum hourly value. These loads were not reduced by any simultaneity factor.

On the contrary, the design domestic hot water (DHW) load was obtained by other means since the hourly values failed to capture the peak load due to its high variability (Averfalk et al., 2021). To overcome this problem, the design flow was estimated according to the recommendations of the Swedish District Heating Association (Energi Företagen, 2016). These provide an expression developed by Holmberg (Holmberg, 1987) for the volumetric flow rate for a number of consumers, n, as shown in Equation (4). It must be noted that these values are considerably more optimistic than the European Standard (CEN-Comité Européen de Normalisation, 2006) or Spanish

Standards (AENOR, 2014, 2017)[1][2] , but measurements by Averfalk or Arvatson (Arvastson & Wollerstrand, 1997) have shown that even the Swedish recommendations deliver too conservative estimates.

$$q_n = q_m + O(n \cdot Q_m - q_m) + A\sqrt{O \cdot q_m}\sqrt{n \cdot Q_m - q_m} \qquad (4)$$

Where

- q_n is the maximum volume flow for n dwellings.
- n is the number of dwellings.
- q_m is the aggregated flow per dwelling (0,15 L/s)
- Q_m is the maximum flow per dwelling (0,2 L/s)
- O is the probability of exceeding q_m (1,5%)
- A is a factor that takes into account the number of times that the design flow is exceeded for n dwellings (2,1).

In the case of service consumers, it was assumed that, on average, their DHW peak demand was the same as the demand from the number of domestic consumers, which occupied the same floor area.

3.1.2 Ultra-low configuration with cold network

The design space heating and domestic hot water loads for each building were extracted from the optimization results of each building described in section 7.7., bearing in mind the heat pump efficiency, the COP. For both uses, space heating and domestic hot water, the maximum load at each consumer was used and no simultaneity factor was considered for either heat use.

In this sense, the heat production units sizing is carried out beforehand and the pipe network dimensioning is executed afterwards. The rationale for this different

[1] The formulae provided by UNE 149201 are merely taken from the German Standard DIN 1988:300 (DIN, 2012).

[2] The Standard UNE 60670-4 is meant to be used for gas installations, but the coincidence factors provided in section 3.3 are widely employed throughout Spanish grey literature on Domestic Hot Water.

approach in relation to the Classic configuration with warm network is that heat production has a higher weight in the Levelized Cost of Heat, heat losses or gains in this configuration are disregarded, and otherwise, additional assumptions would have to be taken to convert the heat demands into design loads.

3.2 Heat Production

This section presents the loads employed for dimensioning the heat production units.

3.2.1 Classic configuration with warm network

In the district-wide production of Configurations I, III, and IV, the total head load for each hour is the sum of the hourly values of space heating and domestic hot water demands, and the pipe network heat losses.

3.2.2 Ultra-Low configuration with cold network

The heat loads used in the sizing of the building heat pumps are directly the hourly space heating and domestic hot water values elaborated in the Enerkad software.

4 System temperatures

In the design of a district heating system, the system temperatures, i.e., the supply and return temperatures, constitute a critical set of parameters. Unfortunately, no systematic study on these parameters has ever been conducted in Spanish networks, and the annual survey of district heating systems (Asociación de Empresas de Redes de Calor y Frío (ADHAC), 2022) does not contain any information on this matter. Nevertheless, anecdotal evidence (Rey-Hernández et al., 2023) suggests that high supply and return temperatures are widespread; for instance, Barcelona's system has a supply temperature of 90°C and return temperatures of 65°C-70°C (Gavaldà-Torrellas et al., 2015).

These high temperatures are likely explained by the widespread use of biomass, which, unlike other sources, does not provide much incentive for temperature reductions (Averfalk & Werner, 2020; Geyer et al., 2021). However, in this study, the considered heat sources were heat pumps and waste heat, whose costs are much more temperature dependent. Therefore, we aimed to use the lowest temperatures we deemed reasonable, but, when deployed, the system should strive to achieve them.

4.1 Domestic hot water preparation and space heating systems

Concerning domestic hot water, the current standard (AENOR, 2023) only obliges to provide a minimum temperature at the tap of 50°C for regular consumers and 55°C for consumers with high hygiene requirements, such as hospitals. Moreover, the temperature must be raised to at least 60°C in the case of accumulation. Hence, if domestic hot water is produced instantaneously with no accumulation, the minimum DH supply temperature could be around 60°C. On the other hand, the district heating return temperature should be below 22°C for the design conditions, according to the Swedish guidelines (Energi Företagen, 2016). Nonetheless, a more conservative value of 40°C has been selected.

Regarding space heating, Spanish systems have been sized for very high temperatures (90°C/70°C) until very recently (Arizmendi Barnés, 1989; Asensio Cerver & Arañó Güell, 1992; CAMPSA, 1992; de Andrés y Rodríguez-Pomatta et al., 1991; Llorens et al., 1998), likely due to the preponderance of fossil fuels in the heating sector and high implicit discount rates. Only after the introduction of the 1998 regulations for thermal installations (Ministerio de la Presidencia, 1998) were the temperatures lowered to (80°C/60°C). Some authors followed suit (Arizmendi Barnés, 2000), but others (Jutglar et al., 2011; Martín Sánchez, 2003) still preferred the higher temperatures so installations design during that period were likely to be suited for the prior temperatures. Later regulations have reduced the average temperature to 60°C in 2013 (Ministerio de la Presidencia, 2013), and the maximum temperature to 60°C in 2021 (Ministerio de la Presidencia Relaciones con las Cortes y Memoria Democrática, 2021).

Therefore, the majority of radiators in the country have been sized for 90°C/70°C or 80°C/60°, and a reduction to lower temperatures (such as 80°C/50°C), which would increase the efficiency of the heat supply and reduce the flows in the network, would decrease the heat emitted by up to a third. Nonetheless, most buildings have undergone a certain degree of energy renovation, and most heating systems are oversized to a certain extent, which would allow a certain reduction of the radiator temperatures (Østergaard, 2018). Additional measures such as the implementation of adequate hydraulic balance (Zhang et al., 2017), the installation of thermostatic valves, the suppression of widespread night set-backs, e.g. (Rey-Hernández et al., 2023), and a more constant operation of the heating systems would also contribute to that temperature reduction (Benakopoulos et al., 2019; Neirotti et al., 2019). Therefore, it was deemed feasible, although somewhat optimistic, to reduce the supply and return temperatures in the space heating systems to 80°C and 50°C, respectively.

4.2 Classic configuration with warm network

Bearing in mind the two heat uses, the district heating supply temperature in configurations I, III, and IV was set to 80°C. The district heating return temperature was assumed to be 50°C when sizing the production units but it is differentiated for dimensioning the district heating network. In this latter calculations, 50°C is assumed for space heating and 40°C for domestic hot water.

In the warm district heating networks (I, III, and IV), the reduction of the forward temperature below 85°C has another benefit since it enables a simplification of the network construction as expansion bends can be avoided to a large extent (AGFW, 2022), which is especially valuable in a dense urban environment.

4.3 Ultra-Low configuration with cold network

In the cold systems, i.e. configurations II and V, the required temperatures for space heating and domestic hot water are provided in each building by means of building or flat heat pumps. These apparatuses exchange heat with the cold network, whose temperatures are close to the ambient temperatures. On the one hand, the supply temperature followed the river temperature since the temperature drop through the heat exchanger was disregarded. One the other hand, the return temperature was linked to the supply temperature by a constant temperature difference, ΔT_{cold}, of 10°C.

This approach is sometimes termed *free-floating* (Wirtz; Neumaier; et al., 2021) and follows other research such as (Zarin Pass et al., 2018). Other authors, such as (Gabrielli et al., 2020) have included a time dependent temperature difference in their optimization problems, but this presents the major drawback of introducing non-linearities since the heat pumps coefficient of performance and the mass flow-temperature difference relation are non-linear.

A higher temperature difference could be advantageous during the summer. First, it would enable free cooling in those buildings with cooling demand and, second, it could reduce water flows in the network with the concomitant pumping savings. During the shoulder seasons the temperature difference could shrink so as to achieve higher COP values in the heat pumps, and hence lower operation costs. However, in the winter peaks the same kind of reduction would necessitate larger pipes in the network in order to cope with the higher mass flows, which would trigger higher investments and probably cancel out the drop in the heat pumps investment.

In summary, a variable temperature difference could facilitate the attainment of the difficult compromise between network and production expenditures. However, due to the likely small effect and increased model complexity, a constant temperature difference was preferred in this study.

4.4 District Cooling

In the district cooling network, present in configuration III, a supply temperature of 6°C and a return temperature of 16°C were assumed (Østergaard et al., 2022). These temperatures are standard in the Nordic countries as illustrated by Swedish (Jangsten, 2020, 2022; Werner, 2017), Danish (Linnebjerg Rasmussen, 2019) or Finnish (Calderoni et al., 2019) experiences. However, more southern systems like Paris' network (Fraîcheur de Paris, 2024) or the network of Barcelona (Districlima, 2022) employ somewhat lower temperatures. Therefore, the 6/16°C regime may be somewhat optimistic and considerable effort would likely need to be exerted so the buildings HVAC systems comply with the design criteria of the district cooling system.

5 Substations

Substations are the necessary element to connect any warm network configuration (I, III, and IV) to each consumer. They produce domestic hot water as well as deliver space heating. In the ultra-low configuration with cold network (II), or the cold combined heating and cooling configuration with cold network (V), the building heat pumps act as substations, so these are unnecessary.

Figure 1 shows the cost of substations according to various recent Spanish projects (López-López, 2022; magnadea, 2019; Tormé-Pardo, 2015; Vallina-Alonso, 2022; Vaquer Martín, 2019, 2022a, 2022b, 2022c, 2022d, 2022e), as well as the Danish Technology Catalogue (Energistyrelsen, 2021). As can be seen in this graph, the equipment cost and, especially, the total cost (including installation) is higher in Spain than in Denmark. These costs are also roughly 40% higher than those provided by a manufacturer (Guðmundsson, 2023) or costs in Italy (Dénarié et al., 2020). Therefore, these estimates were deemed rather conservative and cost reductions would likely be achievable.

The costs presented in Figure 1 were fitted to a linear function in Python with the help of the *iminuit* interface (Dembinski et al., 2020) for the *Minuit* library developed at CERN (James & Roos, 1975). Errors in the fit parameters were calculated after HESSE and corresponded to one standard deviation rather than the more usual 95% confidence interval.

According to the Technology Catalogue, the lifetime of these devices is 25 years, and the annual operation and maintenance costs reach 50 € and 140 €/year for direct and indirect connections, respectively.

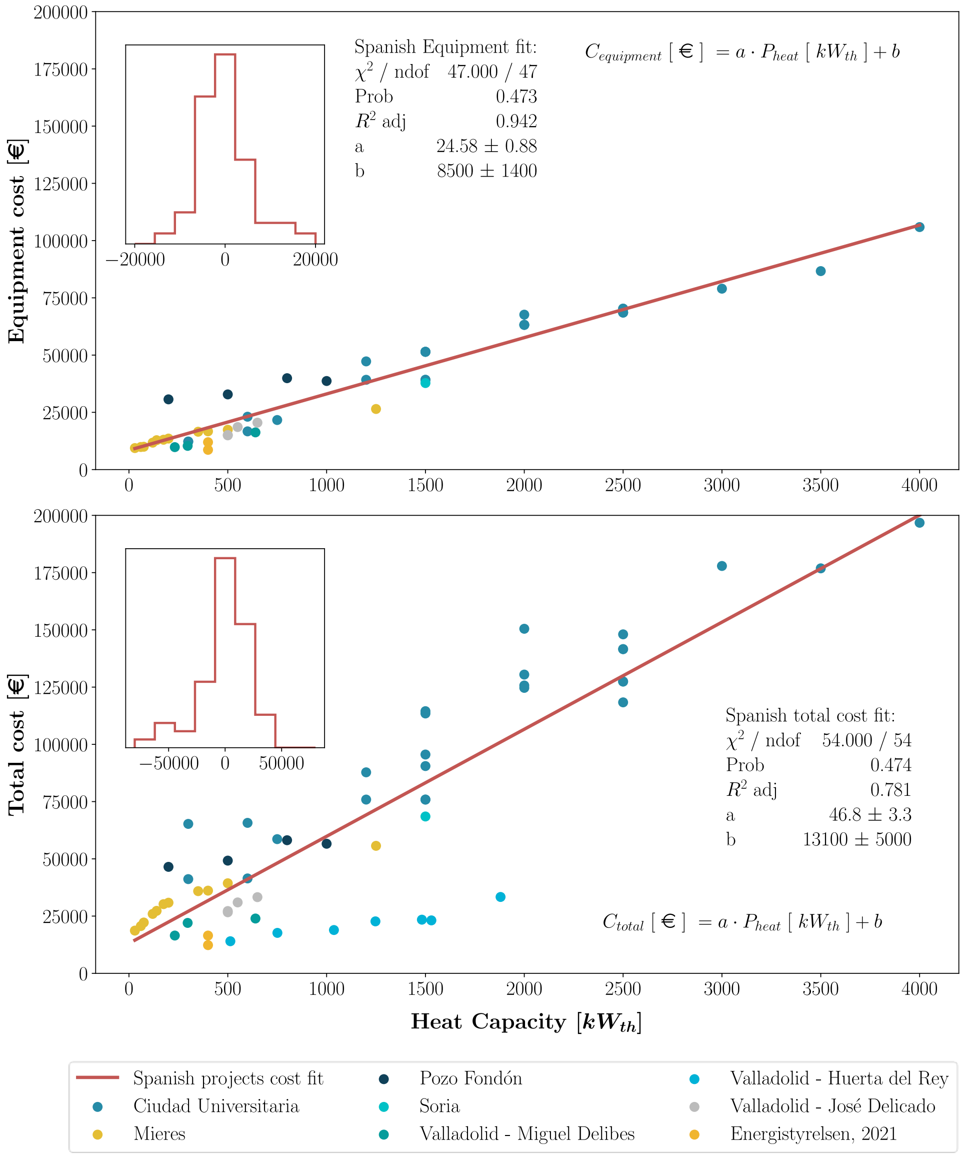

Figure 1. Costs of substations according to various sources [3] [4].

[3] This and subsequent graphs included code developed by Troels Christian Petersen from the Niels Bohr Institute at *Københavns Universitet* for the Applied Statistics course.

[4] This and later graphs were plotted thanks to the Matplotlib library for Python (Hunter, 2007; The Matplotlib Development Team, 2024).

Concerning the connection of individual flats, not only a flat substation would be required but also a raiser pipe from the district heating network to each apartment. This additional pipeline raises the price tag considerably. Experience in Vienna (Wimmer et al., 2020) suggests a cost of 6 000 € per flat, whereas the connection of several buildings in the nearby town of Vitoria was generally achieved with a cost lower than 4 000 € (Arana & Cardenal, 2017; Cervero-Sánchez et al., 2019; Ruiz-de-la-Landa et al., 2020; Ruiz-de-la-Landa et al., 2018; Velasco-Prieto et al., 2018). Therefore, a mean value of 4 000 € was assumed. Furthermore, a lifetime of 25 years and an annual O&M cost of 50 € were assumed.

6 Distribution

This section deals with the methods and data utilized to dimension the pipe networks. Firstly, it is provided a detailed explanation of the methods used for obtaining the network topology as well as the required diameters. This is followed by short exposition of the heat loss calculation methods. Secondly, the necessary data for the pipe systems of the warm and cold configuration is presented.

6.1 Pipe Sizing

The optimization of a district heating network is a mixed integer nonlinear programming problem (MINLP) due to, on the one hand, the integer constraints posed by the placing of the pipes and the discrete commercial diameters and, on the other hand, the non-linearities of heat transport. A good overview of the different methods to tackle this MINLP is provided by (Wack et al., 2022), where approaches range from heuristics or direct resolution (Mertz et al., 2017), to the relaxation of any of the constraints, either the pipe placement (Blommaert et al., 2020) or the physics (Résimont et al., 2021). Another example of this latter relaxation is provided by (Neri et al., 2022), who compares a mixed integer linear programming (MILP) to a heuristic method based on a minimum spanning tree algorithm. Although the MILP leads to a lower cost, the difference is minimal.

Based on the foregoing considerations, and for the sake of simplicity, the design of the network was carried out using a two-step heuristic approach. First, two proposals for the network topology were obtained by application of two different routing algorithms. Second, the pipe diameters were sized to minimize the cost while fulfilling hydraulic constraints. This method did not guarantee the minimum global cost but was likely capable of delivering an acceptable result. Finally, it should be borne in mind that this process rendered a reasonable estimate of the network cost rather than their detailed placing since a wide range of practical aspects, such as street size or location of other utilities, were not considered.

The network's topology was developed in the programming language R (R. Core Team, 2021) with the aid of various packages. In this environment, the raw data was treated with the aim of obtaining a clean street grid, onto which a pipe network could be built. Two sources were used for this task. Firstly, the city buildings obtained from the regional cadastre (Diputación Foral de Vizcaya, 2021) were used to sketch the service pipes. Secondly, the street network, which served as the base for the distribution network, was retrieved from Open Street Maps (OpenStreetMap contributors, 2017) thanks to the *osmdata* package (Padgham et al., 2017).

The service pipes, together with the street network, were subject to a deep pre-processing. In summary, all street edges[5] were subdivided wherever they intersected other edges or wherever another edge was located within a certain distance. For these tasks, the employment of the R packages *sf* (Pebesma, 2018), *lwgeom* (Pebesma et al., 2020) and *dplyr* (Wickham et al., 2022) was instrumental.

After the pre-process was completed, the *sfnetworks* package (van der Meer et al., 2022) was applied to create a non-directed graph. This graph was subject to an additional cleaning process consistent of the removal of duplicated edges and loops, smoothing of *pseudonodes* and removal of disconnected subnetworks, for which the utilization of the *tidygraph* package (Pedersen, 2022) was necessary.

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[5] Throughout this paper, the term *edge* is used as in graph theory, to indicate the line that links two vertices or nodes.

Using the street-based graph, two different strategies were followed to determine the pipe network. The first one aimed to minimise the distance from each consumer to the heat plant, which was accomplished by the routing algorithm provided by *sfnetworks*, based on Dijkstra's algorithm (Dijkstra, 1959). The second one had the minimization of the total pipe network distance as its primary goal. This is the Steiner tree problem in graphs, which was solved by using the approximate algorithm devised by Kou (Kou et al., 1981) and implemented in MATLAB (The MathWorks Inc., 2022). The only difference with respect to Kou's proposal was the utilization of the A* algorithm (Hart et al., 1968) rather than Dijktra's. Although other approximate (Uchoa & Werneck, 2010) or exact algorithms (Hougardy et al., 2017) have been developed for this problem, the simplicity of Kou's heuristic proved to be very attractive.

Once the network topology was established, the elevation of the vertices was extracted from the Spanish Digital Terrain Model (Instituto Geográfico Nacional (IGN), 2022) by means of the *raster* package (Hijmans & van Etten, 2012). After their analysis, elevation data was disregarded in later research, given the limited altitude variation in the area under study.

The last step consisted of the pipe design, which was inspired by the second method devised by Tol and Svendsen, "*The maximum pressure gradient, multi-route method*" (Tol & Svendsen, 2012). In this approach, the head loss gradient is kept approximately constant and limited for each branch of the network tree, so the maximum available head is not exceeded.

Minimizing the pipe diameter leads to both the minimum investments and the minimum heat loss. Conversely, smaller diameters trigger higher pumping costs due to higher head losses. Therefore, a larger diameter than the obtained with Svendsen's algorithm could in principle accomplish lower total costs (investment, heat and heat losses) (Frederiksen & Werner, 2013; Phetteplace, 1995). However, in most cases the minimum cost diameter is smaller than the diameter required not to exceed the available head. Therefore, it is highly unlikely that larger pipe sizes could lead to lower total costs.

The hydraulics of the network were solved following Todini's gradient method (Todini & Pilati, 1989). In this algorithm pressure losses were determined according to Darcy-Weisbach's equation (Darcy, 1856), wherein the Darcy friction factor were estimated by Coolebrook-White's equation (Colebrook, 1939) in the turbulent regime, Poiseuille's law (Poiseuille, 1846) in the laminar regime, and a cubic interpolation between the former two in the transitional regime following (Rossman, 2000). A pipe roughness of 0,1 mm was employed for the steel pipes in the warm network configurations (I, III, and IV) (Frederiksen & Werner, 2013), whilst 0,03 mm was utilized for the PE pipes in the cold network configurations (II and V) (Agüi López et al., 2021).

The minimum pressure in the network was set to 10 meters of water column (mH_2O) (Frederiksen & Werner, 2013), and the pressure loss at the consumers was assumed to be ten mH_2O. Regarding the maximum pressure, two hypotheses were taken, 60 and 100 mH_2O, which would leave certain room for network expansion. In principle, the lower value would also enable the employment of substations with direct connections for space heating, which could bring considerable economic savings, especially in the case of individual flat substations. Unfortunately, as of 2024 this possibility is not permitted by the current Spanish regulations for thermal installations[6] (Ministerio de la Presidencia, 2007) despite these units being widespread in countries with a long district heating tradition, such as Denmark.

6.2 Heat losses

Heat losses were not taken into account for the pipe sizing since temperature drops in peak load situations are negligible (van der Heijde et al., 2017). Nevertheless, their determination was necessary for obtaining the heat load used in heat production optimization of the warm configurations (I, III, and IV).

[6] Article IT 1.3.4.2.1.1. requires hydraulic separation between the district heating network and the buildings' hydraulic installations.

Given the fluctuating temperatures of district heating water and soil, transient heat losses were used. Nevertheless, according to Bøhm (Bøhm, 2000), steady-state formulae (Wallentén, 1991) may be used, provided that the undisturbed soil temperature is taken at the top of the pipe. For this purpose, the undisturbed ground temperature was determined after the formulae presented by (Heller, 2000), assuming a soil diffusivity of 0,054 m^2/day, a thermal conductivity of 2 W/m·K, and a soil cover of 0,5 m. Municipal regulations may demand deeper burying of the pipes (Blanco-Gutiérrez, 2022a), but this assumption was deemed conservative from a heat loss standpoint. Finally, hourly outdoor temperatures were retrieved from the Integrated Surface Dataset (Global) (NOAA National Centers for Environmental Information - U.S. Department of Commerce, 2001).

6.3 Ultra-low configuration with cold network

Concerning the ultra-low configuration with cold network (II), and the cold combined heating and cooling configuration with cold network (V), polyethylene pipes were assumed as these are widely used in the supply of potable water, and there is ample experience in the market.

The regulations of Madrid's water company (Agüi López et al., 2021), which recommend the employment of PE100 plastic, and PN16 pressure class, were followed in this study. Sizes were retrieved from the applicable European Standard (CEN-Comité Européen de Normalisation, 2011) for this pipe type.

The installation cost were estimated based on 14 construction projects for potable water networks in the metropolitan area of Madrid (del-Río-Reyes, 2015a, 2015b, 2016a, 2016b, 2016c, 2016d; Gistau-Gistau, 2015a, 2015b, 2015c, 2016a, 2016b, 2016c, 2016d; López de Celis, 2017). Unlike freshwater networks, district heating grids typically require the laying of two pipes. It was assumed that the cost of earth movements, new pavement, service pipes supplement, and waste management would double, the cost of masonry works, health and safety, and minor works would remain the same, and the cost of pipes and accessories would slightly increase. The cost increase of the pipe material was based on the price differences between ductile cast iron and PE pipes, and the need for two pipes. Furthermore, it was taken into account the fact that the *diamètre nominal* corresponds to rather different inner diameters (CEN-Comité Européen de Normalisation, 2010, 2011). The empirical construction costs, together with the trench length and the average pipe diameter, were used to obtain the linear relationship depicted in Figure 2.

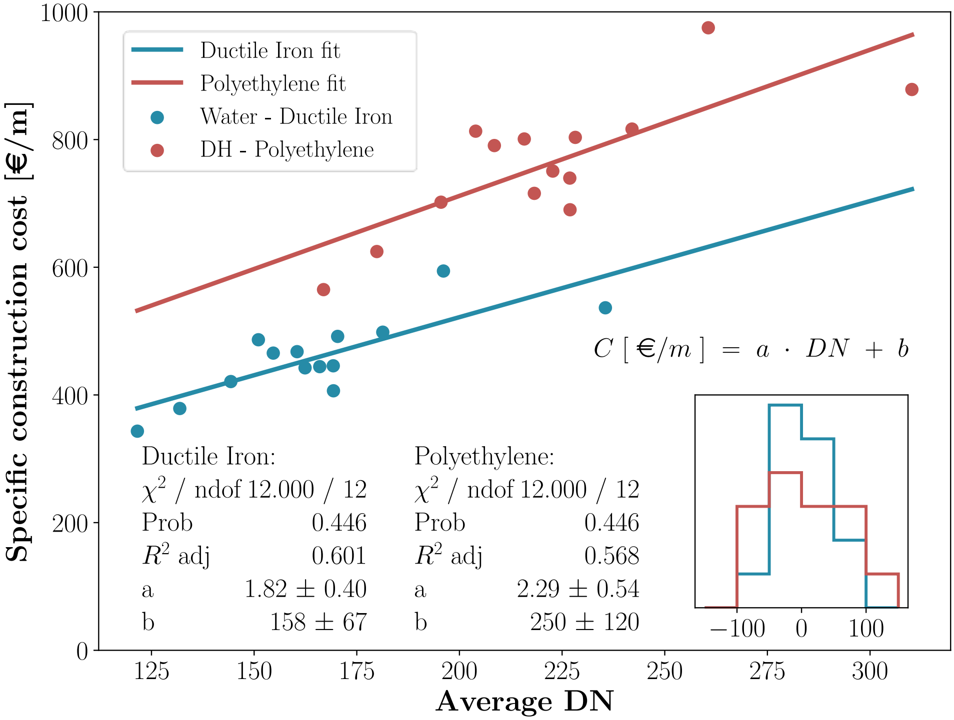

Figure 2. Construction costs of ductile iron potable water networks and polyethylene cold district heating[7].

These installation costs are somewhat higher in the smaller diameters than those presented by these authors in a preliminary version of this study (Sánchez-García et al., 2022), due to the inclusion of additional projects and the slightly different data treatment. Finally, these figures represent a lower cost reduction with respect to conventional district heating pipes than the suggested by (Guðmundsson et al., 2022).

[7] Each dot represents a single project. The average DN was length weighted.

6.4 Classic configuration with warm network

Regarding the warm network configurations (I, III, and IV), it was assumed that twin pipes could be used for diameters smaller than DN200, albeit the lack of prior welding experience in these pipes in Spain (Blanco-Gutiérrez, 2022a) could hinder their deployment. Regardless of the pipe type, Series 2 pipes were preferred since they are state-of-the-art in Scandinavia (Dansk Fjernvarme, 2014). Pipe sizes and insulation properties were taken from the manufacturer Logstor (Logstor A/S, 2022).

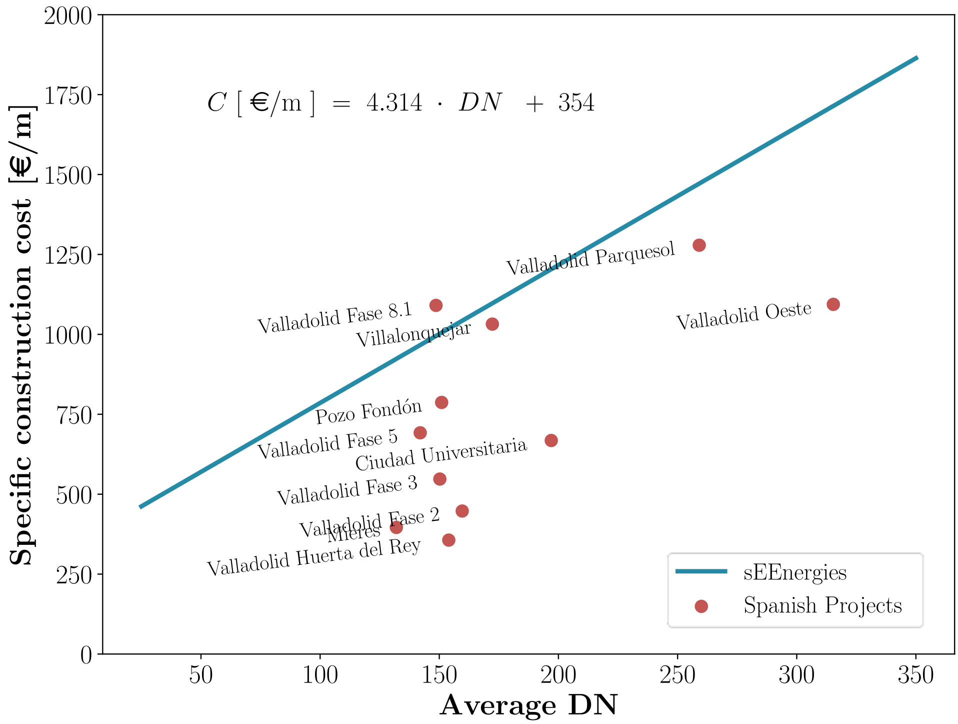

Figure 3. Construction costs of district heating pipes in Spain.

Installation costs[8] for district heating pipes are usually related to the pipe diameter by a linear function (Persson & Werner, 2011). The cost curve provided by the sEEnergies project (Persson et al., 2021), shown in Figure 3, was used in this study.

[8] Including the purchase of the pipe, its welding, and all the civil works.

Nevertheless, it must be noted that the construction costs predicted by this curve are rather conservative in light of recent projects in Spain (Blanco-Gutiérrez, 2020a, 2020b, 2022f, 2022g, 2022h, 2023; López-López, 2022; magnadea, 2019; Tormé-Pardo, 2015; Vallina-Alonso, 2022; Velázquez-Pacheco, 2023) or the recently published comprehensive assessment (Ministerio para la Transición Ecológica y el Reto Demográfico & Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2023), and a certain cost reduction would likely be possible.

6.5 District Cooling

A district cooling network is considered in one of the sensitivity analyses, the warm combined heating and cooling configuration with warm network (III). In this network the same piping costs as those presented in section 6.4 were used. This is, no cost reduction due to synergies for simultaneous construction were assumed despite the second comprehensive assessment on district heating and cogeneration suggesting a 1/3 cost-saving potential (Ministerio para la Transición Ecológica y el Reto Demográfico & Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2023).

7 Production

This section addresses the methods and data required for the sizing of all the heat production equipment. Firstly, an overview of the problem is provided, followed by a detailed account of data on energy prices, heat pumps, gas boilers and thermal energy storage. The section finalises with a brief description of the optimization problems for configurations I and II. A more thorough description of the mathematical programming problems of all configurations (I, II, III, IV, and V), is provided in the supplementary material.

7.1 Overview

The city of Bilbao is surrounded by several industrial facilities, which could supply abundant waste heat to the city. Among these are the oil refinery of Petronor, the cement factory of Rezola Arrigoriaga, and the incineration plant of Zabalgarbi, which, in total, could roughly deliver 600 GWh (Möller et al., 2022). This amount of heat is an order of magnitude higher than the heat demand in the area under study. However, the distance from the nearest plant, approximately 7 km, precludes its cost-effective exploitation until the supply area is expanded beyond the area under analysis[9]. Therefore, it was decided to use heat pumps fed by river water as the primary heat source for the district heating solutions. Moreover, for the warm network configurations (I, III, and IV), the production plant was backed up by a gas boiler.

A key parameter in the operation of a heat pump is the coefficient of performance (COP), which relates the heat output to the electricity input. This parameter may be determined by different methods ranging from as simple as the Lorenz COP presented by (Reinholdt et al., 2018) and used by the Danish Technology Catalogue (Energistyrelsen, 2018) to full thermodynamic models (Pieper et al., 2020) or intermediate approaches (Jensen et al., 2018). Although a thermodynamic model or the method by Jensen et al. would deliver the most accurate COP estimations (Pieper et al., 2020), they require detailed knowledge of the heat pump configuration and refrigerant, which, at the stage of this study, was unknown. Therefore, the most straightforward Lorenz COP was primarily used in this study.

$$COP_{real} = \eta_{Lorenz} \cdot COP_{Lorenz} = \eta_{Lorenz} \cdot \frac{\Theta_H}{\Theta_H - \Theta_C} \tag{5}$$

$$\Theta = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)} \tag{6}$$

The Lorenz COP was calculated according to Equation (5), where COP_{real} is the real coefficient of performance, η_{Lorenz} is the Lorenz efficiency, COP_{Lorenz} is the theoretical Lorenz COP and Θ_H and Θ_C are respectively the logarithmic mean temperature difference of the heat sink and source. These logarithmic mean

[9] Economies of scale in heat transmissions are clearly illustrated in Figure 22 of IRENA's guideline (Angelino et al., 2021).

temperature difference may in turn be calculated according to Equation (6). In this latter equation, T_{in} is the inlet temperature to the heat pump, either the return temperature from the heating system or the source's temperature, and T_{out} is the outlet temperature of the heat pump, either the heating system supply temperature or the temperature of the heat source after releasing its heat.

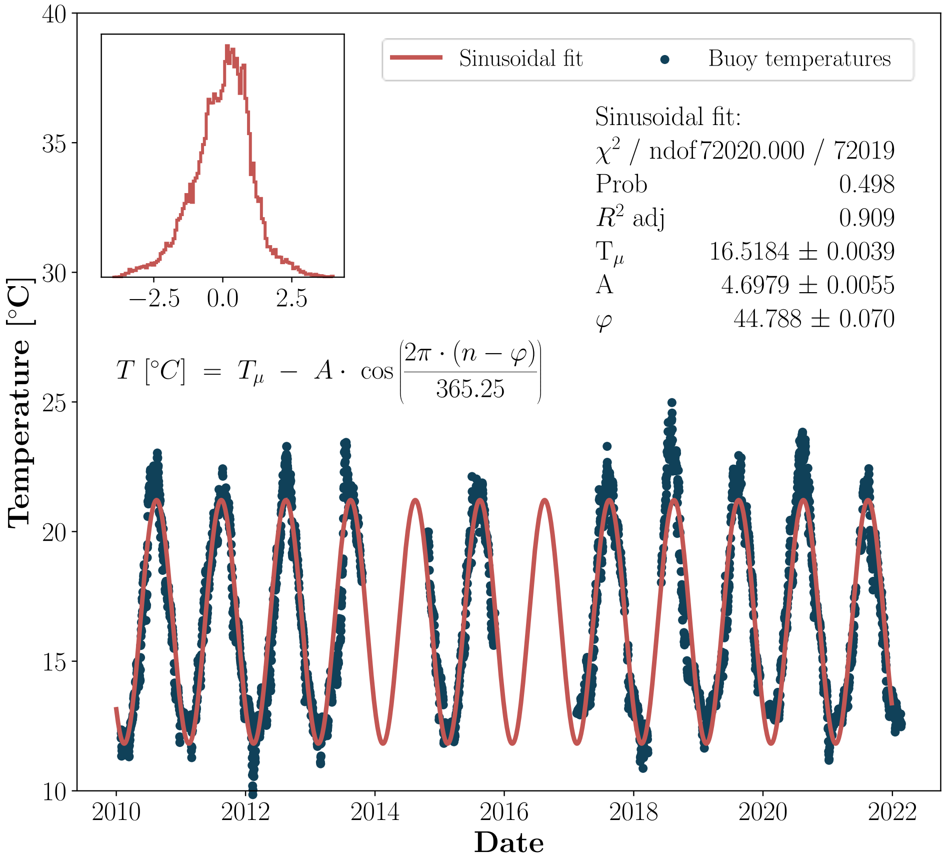

Figure 4. Sea temperatures in the port of Bilbao.[10] [11]

In all the configurations the heat source was the nearby Nervión estuary, whose tide limit is upstream of the city (Borja et al., 2004). Since water temperatures were not

[10] The regression analysis has been carried out using all the hourly values, but the scatter plot only contains daily means in order to reduce the figure's size.

[11] In the temperature equation, the variable n stands for the day of the year.

found in the town, water temperatures at the port of Bilbao (Puertos del Estado, 2022), located in the mouth of the estuary, were used as a proxy. It must be noted that although a salty wedge is always present at the bottom of the estuary (Valencia et al., 2004), the residence time is rather long, in the order of weeks (Garmendia et al., 2012). Hence, the port temperatures were a mere approximation.

The Spanish port authority provided hourly temperatures for the period 2010-2022, albeit with numerous missing values, as shown in Figure 4. This issue, along with the aim to obtain an average situation, led to fitting a simple sinusoidal curve from which the average water temperature could be obtained at any given time of the year.

Hydraulic separation between the estuary and the district heating equipment would be necessary in an actual implementation of any of the proposed configurations. However, in this study the temperature drop through the heat exchanger was disregarded.

7.2 Energy Prices

The energy sources employed for the heat production were electricity and natural gas. Regarding electricity, spot prices, which are shown in Figure 5, were retrieved from the Spanish transmission system operator (TSO), *Red Eléctrica de España*, (Red Eléctrica de España, 2022a). In addition, network fees and charges were obtained from the Spanish official gazette (Comisión Nacional de los Mercados y la Competencia, 2020, 2021; Ministerio para la Transición Ecológica y el Reto Demográfico, 2021), and other supplementary fees were found in (Pereira Pérez, 2020).

Importantly, these fees and electricity grid losses depend on the voltage level of the consumer[12]. Based on the likely voltage levels at each type of consumer, the rate 3.0 TD[13] was selected for the building heat pumps in configurations II, IV, and V, and the

[12] For instance, the Tanger Production Plant of Barcelona's district heating system receives its electricity at 45 000 V, which is transformed to 6 000 V to feed the electric chillers.
[13] The rate 3.0 TD is used by low voltage consumers (up to 1 000 V) and electric powers higher than 15 kW.

rate 6.3 TD[14] was chosen for the district heat pump in configurations I, III, and IV. Given the rather complex structure of the Spanish electricity costs, an overview has been included in the supplementary material.

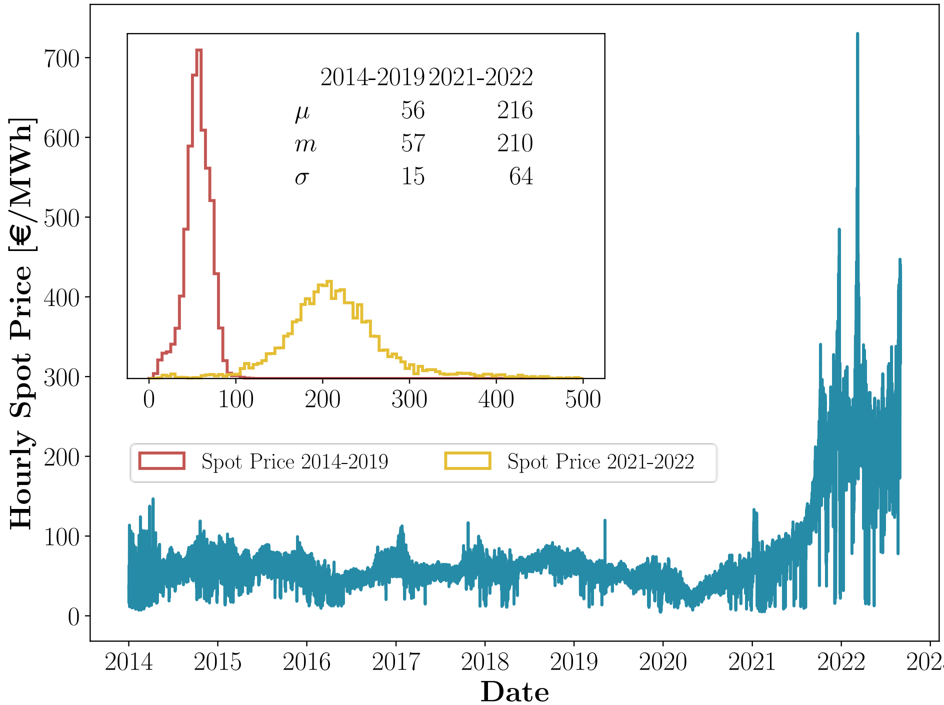

Figure 5. Spot prices in the Spanish market.

Even though spot prices were used for all the network configurations, the electricity price at the heat pump differed because of two components. On the one hand, the electricity buyer must purchase the gross electricity demand, including electricity grid losses, which are different for the two voltage levels. The building heat pumps borne low-voltage grid losses ranging from 13,8% to 18%, whereas the district-wide heat pump only had to cover high-voltage grid losses ranging from 3% to 4,3%. On the other hand, energy-related network fees and charges are between 3,5 to 4 times higher in the 3.0 TD tariff. The effect of these factors can be appreciated in Figure 6, where

[14] The rate 6.3 TD is used by high voltage consumers (30; 72,5) kV.

cold configurations clearly bear higher electricity prices than the warm configurations, especially during the high season months and peak hours.

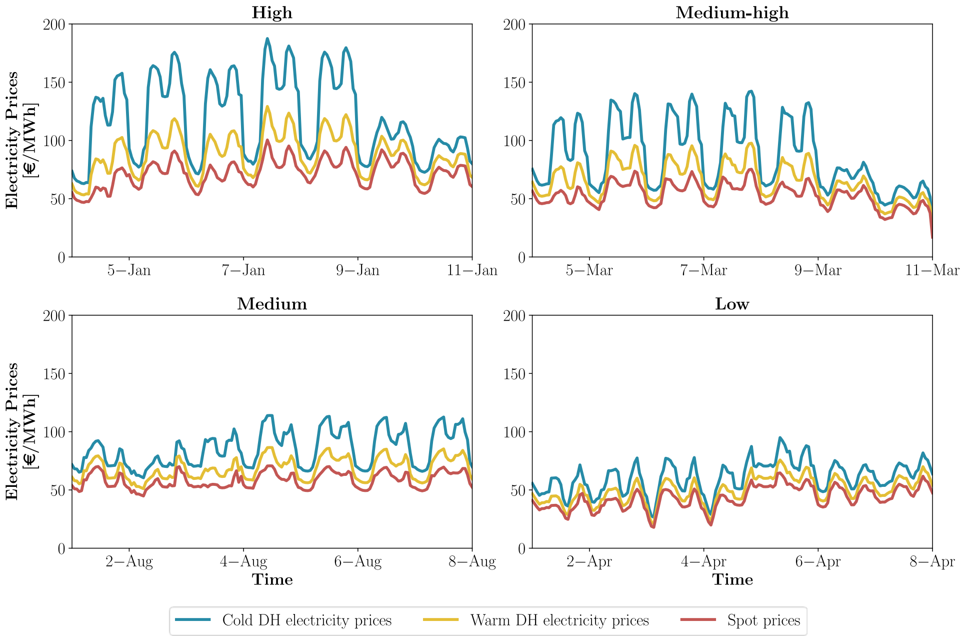

Figure 6. Electricity prices at the district-wide heat pumps for the warm configurations (I, III, and IV) and at the building heat pumps for the cold configurations (II and V) and the building chillers in configuration IV.

The heat production of the warm network configurations (I, III, and IV) was based on the entire spot price series from 2014 to 2020, whereas each building unit of the cold network configurations (II and V) was optimised based on a synthetic annual price series. The rationale for this choice was to reduce the computation time in the cold configurations.

The synthetic annual price series was constructed following the same methodology as for the meteorological Test Reference Year (CEN-Comité Européen de Normalisation, 2005; Lee et al., 2010). In this approach each month of the synthetic year was selected as the closest to the long-term average month of 2014-2020.

The regulated PVPC rate (Ministerio de Industria, 2014; Roldán-Fernández et al., 2017), retrieved from the Spanish TSO (Red Eléctrica de España, 2022b), was used to determine the energy cost of both the flat air-to-water heat pumps and the water-to-water flat heat pump in configuration II.

Concerning gas prices for district heating production, a constant price of 100 €/MWh was assumed, which was relatively higher than the historical averages[15]. Still, it could represent a long-term future average accounting for the cost of carbon or the production cost of biogas[16] (Energistyrelsen, 2014).

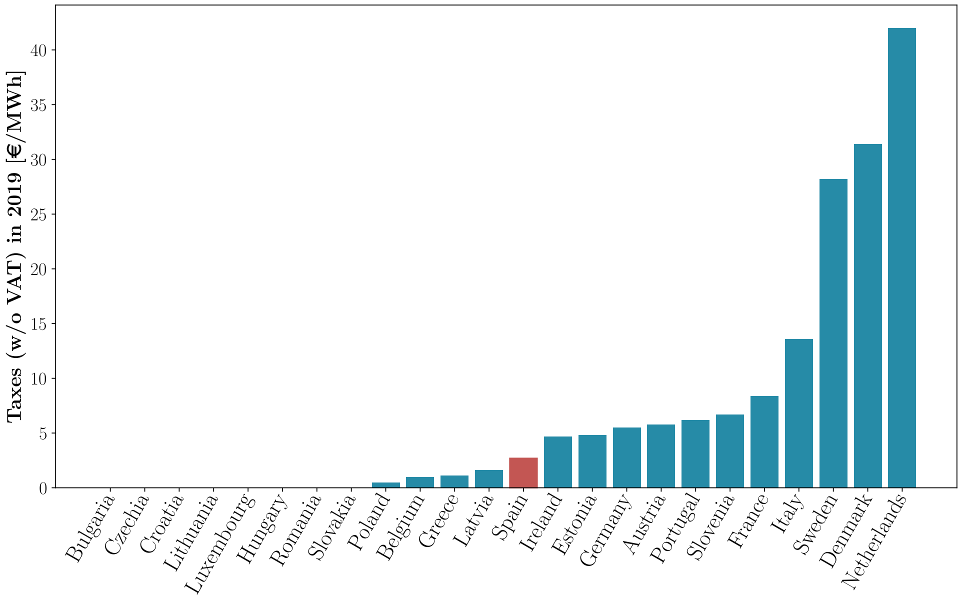

Figure 7. Taxation (excluding VAT) on natural gas on EU Member States in 2019. Source: (European Commission, 2023a)

The cost of natural gas for building gas boilers was obtained from Eurostat (band D3) (European Commission, 2023c), whereas the regulated TUR[17] rate (Ministerio de

[15] Historical prices of natural gas were obtained from Eurostat, using both the energy price and international commerce statistics. Values are provided in the supplementary material.
[16] According to *Energistyrelsen*, the cost of upgraded biogas was 160 DKK/GJ in 2014; approximately 80 €/MWh, without accounting for inflation.
[17] The regulated TUR rate has consistently been cheaper than the mean price values indicated by Eurostat. Unfortunately, this rate is only available for consumers with annual energy demands below 50 000 kWh.

Energía Turismo y Agenda Digital, 2016, 2017a, 2017b, 2017c, 2017d, 2018; Ministerio de Industria, 2015a, 2015b, 2015c; Ministerio de Industria Energía y Turismo, 2013, 2014, 2015, 2016a, 2016b; Ministerio para la Transición Ecológica, 2018a, 2018b, 2018c, 2019) was used for flat gas boilers. For both types of consumers, the retail prices comprise all the cost components, this is, not only, the raw energy source, but also other outlays such as transport costs and commercialization expenses. Furthermore, all taxes but the Value Added Tax have been included. The low values are explained by the low taxation of natural gas in the country, compared to its European counterparts as shown in Figure 7.

7.3 Heat Pump

Costs of large heat pumps were retrieved from Pieper and the Danish Technology Catalogue (Energistyrelsen, 2018; Pieper, 2019), and were related to both heat and electrical capacities by means of linear functions, as shown in Figure 8. In this figure it can be appreciated that the coefficients obtained from the two sources are not very different, although *Energistyrelsen*'s curves are slightly more conservative. Experience from Spain was scant (magnadea, 2019; TPF-GETINSA-EUROESTUDIOS, 2018) and could not provide a clear trend since the difference in cost in the two projects ranges from 70% cheaper to 50% more expensive.

The investment costs of small water-to-water heat pumps were extracted from the database maintained by the company CYPE (CYPE Ingenieros S.A., 2022p) and were similarly correlated to the heat and electric capacities. The resulting equation delivered lower results than the Danish values (Energistyrelsen, 2021), although the latter also includes the cost of a horizontal collector. However, similar unit costs are provided by (Jebamalai et al., 2022; Vivian et al., 2018).

The cost of flat air-to-water heat pumps typically ranges from 5 000 to 10 000 € according to (CYPE Ingenieros S.A., 2022i, 2022j, 2022k, 2022l, 2022m, 2022n, 2022o), after which a conservative value of 6 000 € was selected. Similarly, the cost of building air-to-water heat pumps was based on various sources, including actual projects (Energistyrelsen, 2021; García Rodríguez, 2022; Gastaminza Santa Coloma &

Uranga Royo, 2019; Hernández-Iñarra et al., 2019; Hernández Iñarra, 2022a, 2022b; Varona Peña & Aguilar García, 2019). Unfortunately, not many projects of building heat pumps could be obtained, which led to considerably ample confidence intervals in the equation coefficients.

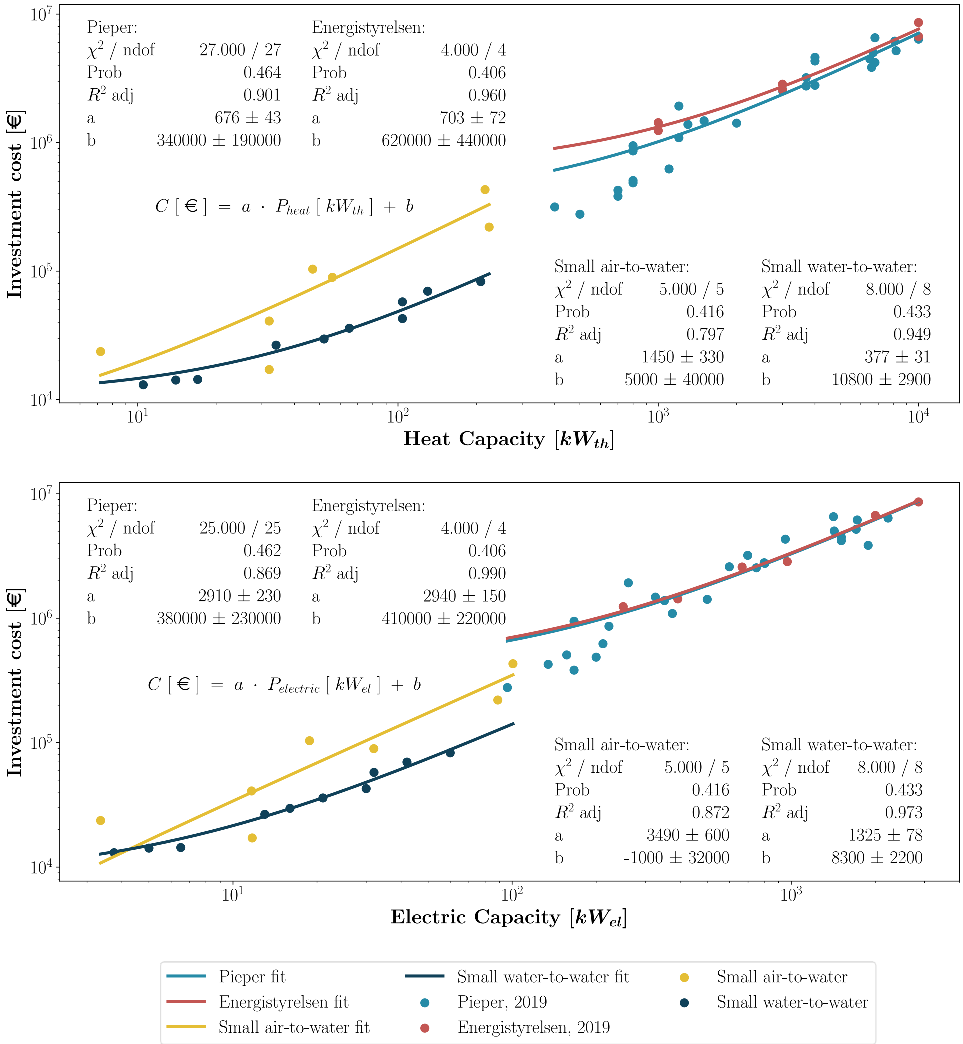

Figure 8. Cost of large and small heat pumps.

In all the cases, both the technical lifetimes, and annual operation and maintenance costs were based on the Danish Energy Agency's Technology Catalogue (Energistyrelsen, 2021).

7.4 Gas boiler

The cost of gas boilers for district heating were obtained from the Danish Technology Catalogue (Energistyrelsen, 2018), whereas the database by CYPE (CYPE Ingenieros S.A., 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g) was used for the building and individual gas boilers. The assumed costs of the building gas boiler were significantly lower than those indicated by (Hernández-Iñarra et al., 2019). In all the cases the lifetime was taken from *Energistyrelsen*, whereas the O&M costs were retrieved from the same sources as the investment costs.

7.5 Thermal Energy Storage

A water tank was chosen as thermal energy storage (TES) given its cost-effectiveness, ample use by district heating systems, and fast charge and discharge rates. The cost of this installation was estimated based on a linear function of the tank volume. This equation was initially fitted with Danish data from the Flexynets project (Sveinbjörnsson et al., 2019), which are slightly higher than those provided by the Danish Technology Catalogue (Energistyrelsen, 2025). This discrepancy was likely due to the year difference since *Energityrelsen*'s data were originally published in 2013 (PlanEnergi et al., 2013). However, the intercept was half of the one that could be estimated from Gadd's data (Gadd & Werner, 2015, 2021) or what could be extrapolated from several recent Spanish (Blanco-Gutiérrez, 2022b, 2022c, 2022d, 2022e) or Danish projects (Dansk Fjernvarme, 2022a, 2022b)[18]. Furthermore, the main driver of water tank cost is steel prices (Energistyrelsen, 2018), which in 2022 increased by roughly 60-70% compared to the average of the prior decade (European

[18] The costs of the two Danish projects are 270 and 470 €/m^3 for sizes of 50 000, and 2 000 m^3, respectively and the costs of the Spanish projects are 400, and 535 €/m^3 for sizes of 6 000, and 3 500 m^3, respectively.

Commission, 2022; Instituto Nacional de Estadística (INE), 2022)[19]. Therefore, the coefficients derived from Gadd's data were employed to be on the safe side.

The equipment and installation costs for small water tanks were retrieved from the construction cost database maintained by CYPE (CYPE Ingenieros S.A., 2022h). Although the dataset includes the cost of several manufacturers, the average manufacturer was used in this investigation. The data, as well as the linear fit, are plotted in Figure 9, where economies of scale between water tank types can be clearly appreciated.

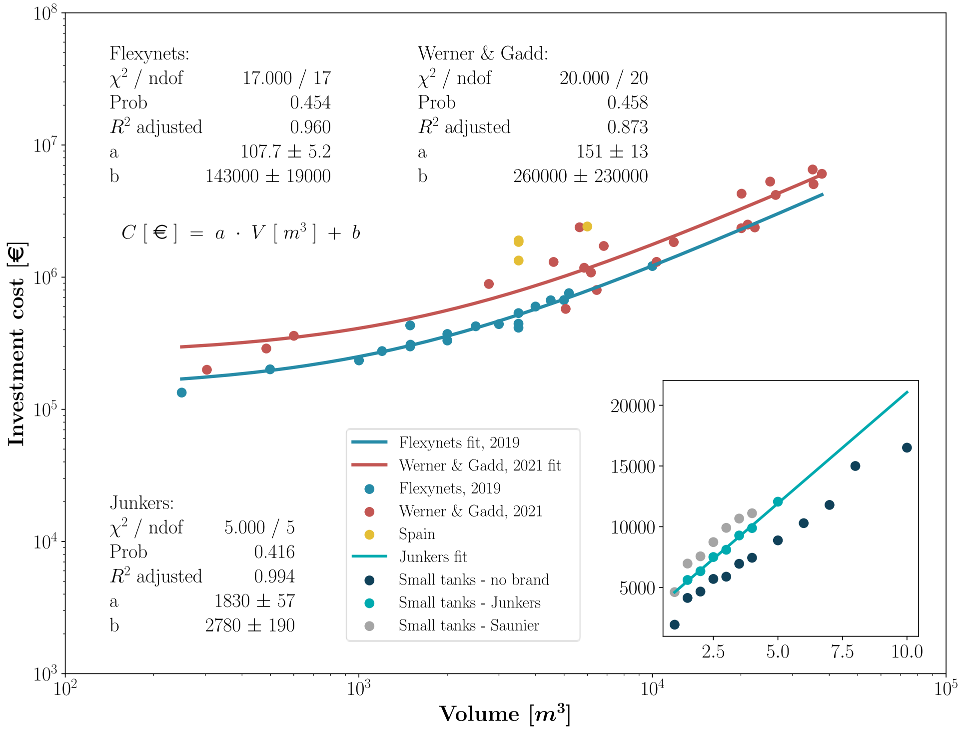

Figure 9. Investment cost for small and large water tanks.

The district-wide heating plant, alongside the thermal storage, was placed in the park located near the river, where water for the heat pump could be easily extracted.

[19] Average steel prices were estimated based on the amounts and value of the steel imports and exports from and within the European Union (UE-27) (European Commission, 2022). Spanish prices correspond to steel materials used in the construction industry (Instituto Nacional de Estadística (INE), 2022).

Given the visual impact that such a construction has, we assumed it to be built underground, similar to *Fraîcheur de Paris*' district cooling plant by the river Seine. Thus, estimating the cost of digging a pit for the steel tank was necessary. In this estimation, a circular diaphragm wall shaft was assumed due to its properties.

These circular diaphragm wall shafts have been extensively used during the construction of Barcelona's line 9 metro stations (Deulofeu Palomas, 2013; Laguna & Pérez, 2019; Vicario Lara, 2004), reaching depths of 75 metres with diameters between 26 and 33 metres. Despite meticulous effort[20], it was not possible to retrieve any original construction project from which to extract cost estimates of the shaft cost. Fortunately, a feasibility study of alternatives (López-Pozo, 2011) provided an estimate of the required construction units[21] and volumes, which were subject to further analysis. On the one hand, unit prices were updated to 2021 thanks to the construction cost database of the Catalan administration (Generalitat de Cataluña, 2021). On the other hand, the required unit volumes for different pit sizes were estimated. All unit amounts were directly proportional to the cylinder's volume, lateral or upper surface, except for the thickness of the concrete wall. This latter depended on the diameter of the shaft, the maximum pressure exerted by the ground (Virollet et al., 2006) as well as the yield stress of the concrete.

The result of these calculations, whose details may be explored in the supplementary material, was the expression (7), where C, is the cost of the pit, [€], H, is the depth of the pit, [m], D, is the diameter of the pit, [m], and α, β, γ, and ε are

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[20] Spain usually follows the design-bid-build method and the construction project carried out by the administration or the engineering firm is released during the tender. However, due to the time passed, these documents are no longer available.

[21] Civil construction projects in Spain are itemized; this is, the budget is elaborated as the sum of the product of individual unit prices and unit volumes. A construction unit is for instance the extraction of a cubic meter of earth in a shaft, the installation of a kg of steel armour or a square meter of formwork. These unit prices are calculated factoring in all the input costs, such as material, labour, machinery or transport costs. Additionally, fixed percentages accounting for overhead and contractor *fair* profit are added to the project. This method is illustrated in Figure 7 of the Italian case study report of the Transit Cost Project by Goldwyn et al. (Goldwyn et al., 2023).

coefficients with the values of 1 922 €, 1 724 €/m², 41,06 €/m³ and 3,389 €/m⁴, respectively.

$$C = \alpha \cdot D + \beta \cdot D^2 + \gamma \cdot H \cdot D^2 + \varepsilon \cdot H^2 \cdot D^2 \tag{7}$$

Equation (7) was reformulated as a function of the volume, V, and the ratio between the height and the diameter of the water tank, ϕ. Furthermore, if both the cost of the pit and the tank were considered, equation (8) was reached. Although for large volumes (>5 000 m³), lower ϕ ratios led to lower unit costs as illustrated in Figure 10, for the volumes under consideration in this study, the influence of this ratio was minimal, and hence, a ratio of two was assumed, as recommended by (Energistyrelsen, 2025; Thomsen & Overbye, 2015).

$$C_T = C_{pit} + C_{tank} = \left(\alpha\left(\frac{4V}{\pi\phi}\right)^{\frac{1}{3}} + \beta\left(\frac{4V}{\pi\phi}\right)^{\frac{2}{3}} + \gamma\frac{4V}{\pi} + \varepsilon\phi^2\left(\frac{4V}{\pi\phi}\right)^{\frac{4}{3}}\right) + (mV + n) \tag{8}$$

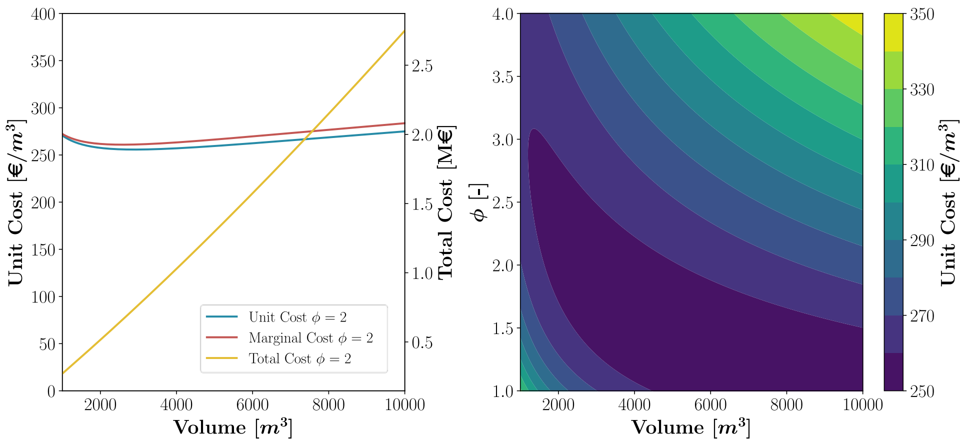

Figure 10. Unit cost, marginal cost and total cost as function of the pit volume and shape factor.

Finally, the derivative of the total cost function with respect to the volume was used to estimate the optimal thermal storage size. Unlike the tank, which had a constant derivative, the pit's is not constant but varies very little over the possible size range, and, for the sake of simplicity, it was assumed as constant.

7.6 Classic configuration with warm network

The optimal sizing of the heat pump, accumulation tank and the dispatch of the units was carried out by means of linear programming inspired by the formulation by Dorotić (Dorotić et al., 2019). This approach was chosen due to its simplicity and the rather good results compared to more elaborate formulations (Wirtz; Hahn; et al., 2021). Specifically, no part-load limitations and efficiencies, non-linear investment curves or ramping constraints were considered. Wirtz shows that the inclusion of these aspects does not significantly alter the results but cause a higher model complexity and significantly higher computation times. Hence these refinements were disregarded so as to simplify the models and accelerate resolution.

The main differences with respect to Dorotić's model related to the inclusion of the thermal storage's heat losses, which were determined in a similar fashion to (Åberg et al., 2019), although with negligible impacts, and the inclusion of the distinctive features of the Spanish electricity fees. Not only do these levies depend on the energy used (€/MWh), but also on when it is used according to six periods, and the maximum power that may be utilised in those periods (€/MW), regardless of the actual energy usage.

The problem was formulated in MATLAB according to Equations (9) to (17). In this set of equations the following variables were employed: ${Q_{NG}}_i$ and ${Q_{HP}}_i$, which stood for the heat production from the gas boiler and the heat pump, respectively, in each hour; P_j, the contracted power in each period j; $P/Q_{HP_{max}}$, the electric or thermal capacity of the heat pump; TES_{max}, the size of the thermal storage, and ${Q_{TES_{in}}}_i$ and ${Q_{TES_{out}}}_i$, the loading and unloading of the thermal energy storage (TES) in each hour.

Unlike the heat pump, the capacity of the gas boiler was not optimised as it was assumed to have the additional function of back-up and its capacity was set to be equivalent to the maximum daily load.

The objective function, illustrated by Equation (9), represented the annual cost of heat supply. On the one hand, the first three terms corresponded to the annual cost of natural gas, electricity (MWh), and electric capacity (MW), including both the energy outlays and the variable operation and maintenance expenditures. On the other hand, the last two terms represented the annualised capital and fix maintenance costs of the heat pump and steel tank.

The remaining equations accounted for the various technical constraints such as the balance between supply and demand, (10); maximum production of the heat pump, (11); state of charge of the Thermal Energy Storage, (12); maximum charge of the TES, (13); cyclic condition for the TES, (14); maximum charge or discharge rates for the Thermal Energy Storage, (15); maximum electricity demand of the heat pump in each power period, (16); and the relationship between the maximum power consumption in the various periods according to the Spanish regulations (17). Aside from these equations, additional inequality constraints ensured all variables to be positive.

The Linear Programming problem was solved under two different formulations; in the first one, the heat pump electric power, $P_{HP_{max}}$, was assumed to be the optimized variable, and the heat production varied according to the COP; in the second one, the maximum heat capacity, $Q_{HP_{max}}$, was assumed to be the design criterion and the electricity use changes following the COP. These two formulations resulted in slightly different equations (9) and (11). The first formulation was inspired by EnergyPRO (EMD International A/S, 2022), whereas the second was based on the work by Bach and Pieper (Bach, 2014; Pieper, 2019).

$$C_T = \sum_{i=1}^{\tau} c_{NG_i} \cdot Q_{NG_i} + \sum_{i=1}^{\tau} c_{HP_i} \cdot Q_{HP_i} + \sum_{j=1}^{n} c_{P_j} \cdot P_j + (a \cdot I_{HP} + O\&M_{HP}) \cdot P||Q_{HP_{max}} + a \cdot I_{TES} \cdot TES_{max} \quad (9)$$

$$Q_{DH_i} = Q_{NG_i} + Q_{HP_i} - Q_{TES_{in_i}} + Q_{TES_{out_i}} \tag{10}$$

$$Q_{HP_i} \leq COP_i \cdot P_{HP_{max}} \; || \; Q_{HP_i} \leq Q_{HP_{max}} \tag{11}$$

$$TES_i = TES_{i-1} + Q_{TES_{in_i}} - Q_{TES_{out_i}} - \eta_1 - \eta_2 \frac{1}{2}(TES_i + TES_{i-1}) \tag{12}$$

$$TES_i \leq TES_{max} \tag{13}$$

$$TES_1 = TES_\tau \tag{14}$$

$$Q_{TES_{x_i}} \leq Q_{TES_{max}} = \frac{TES_{max}}{t_{charge_{min}}} \tag{15}$$

$$\frac{Q_{hp_i}}{COP_i} \leq P_j \tag{16}$$

$$P_j \leq P_{j+1} \tag{17}$$

Where:

- i, Time step, an hour.
- τ, Optimization horizon.
- j, Period number in the Spanish electricity system.
- n, Number of network fee periods in the Spanish electricity system (6).
- C_T, Total annualised cost to be minimised.
- c_{NG_i}, Marginal cost of heat from the natural gas boiler i including variable O&M, fees and charges and non-recoverable taxes. [€/MWh_{th}]
- c_{HP_i}, Marginal cost of heat from the heat pump in hour i, including variable O&M, fees and charges and non-recoverable taxes. [€/MWh_{th}]
- Q_{NG_i}, Heat produced by the natural gas boiler in the hour i. [MWh_{th}]
- Q_{HP_i}, Heat produced by the heat pump in the hour i. [MWh_{th}]

- c_{P_j}, Cost of network fees and charges in the period j. [€/MW$_{el}$]
- P_j, Maximum electric power that the heat pump can consume in period j. [MW$_{el}$]
- a, Annuity ratio. [-]
- I_{HP}, Marginal investment cost for the heat pump [€/MW$_{el}$ or €/MW$_{th}$]
- $O\&M_{HP}$, Fix Operation and Maintenance expenses [€/MW$_{el}$ or €/MW$_{th}$]
- $P \,||\, Q_{hp_{max}}$, Electric or thermal capacity of the heat pump. [MW$_{el}$ or MW$_{th}$]
- I_{TES}, Marginal investment cost for the Thermal Energy Storage [€/MWh$_{th}$]
- TES_{max}, Thermal capacity of the Thermal Energy Storage [€/MWh$_{th}$]
- $Q_{TES_{x_i}}$, Heat loaded into the Thermal Energy Storage, $Q_{TES_{in_i}}$, or unloaded $Q_{TES_{out_i}}$. [MWh$_{th}$]
- η_1 & η_2, Heat loss coefficients for the Thermal Energy Storage [MWh$_{th}$ and -]
- COP_i, Coefficient of Performance of the heat pump in the hour i. [-]
- $t_{charge_{min}}$, Minimum charge and discharge time for the Thermal Energy Storage [h]

7.7 Ultra-Low configuration with cold network

As explained before, the heat supply in the cold network was delivered by distributed heat pumps connected to water tanks at each building. Unlike Wirtz (Wirtz et al., 2020), who simultaneously optimises all the buildings' heat pumps, in this study, each building was analysed separately, neglecting the possible influence between each other.

Since the necessary temperatures for space heating and domestic hot water production differ, it was assumed that the heat pump produced either space heating or domestic hot water at each respective temperature, possibly storing the output in separate thermal energy storages. This "either" constraint required solving the dimensioning and dispatching problem through mixed integer linear programming (MILP). In four buildings, characterised by a significant heat demand, the MILP problem proved unfeasible. In these four buildings the MILP unfeasibility led to the employment of two separate heat pumps, one for each heat use, and the same Linear Programming formulation as for the Classic Configuration with warm network for each demand. This latter approach was not applied to all the buildings due to space constraints in the buildings' boiler rooms. Furthermore, this issue also motivated an upper limit of 5000 L for each water tank.

The mixed integer linear programming problem was formulated in MATLAB and solved with Gurobi (Gurobi Optimization LLC, 2023) due to its much higher speed. In this problem, Equation (18) showed the objective function, which in this case excluded a gas boiler but included the separation of the heat load in its two components, domestic hot water and space heating, since they were fulfilled by the heat pump separately. In addition, Equations (19) to (23) showed the technical constraints that were substantially different from the constraints (10)-(17). For the sake of brevity, constraints related to supply, maximum heat production of the heat pump or thermal storage operation were omitted here.

The most relevant difference with respect to the LP optimization problem lied in the alternate supply of domestic hot water and space heating by the heat pump. Three sets of equations addressed this issue; first, the binary variables δ_{DHW_i} and δ_{SH_i}, which indicated whether the heat pump produced the respective product (1) or not (0) in Equations (19) and (20); second, the constraint that the heat pump produced either domestic hot water or space heating, (20); third, the big-M constraints in Equations (22) and (23), which ensured that the heat production was zero when the respective binary variable was zero.

$$
\begin{aligned}
C_T = \sum_{i=1}^{\tau} c_{HP_{DHW_i}} \cdot Q_{HP_{DHW_i}} + \sum_{i=1}^{\tau} c_{HP_{SH_i}} \cdot Q_{HP_{SH_i}} + \sum_{j=1}^{n} c_{p_j} \cdot P_j \\
+ (a \cdot I_{HP_{max}} + O\&M_{HP}) P_{HP_{max}} + a \cdot I_{TES_{max}} \\
\cdot TES_{DHW_{max}} + a \cdot I_{TES_{max}} \cdot TES_{SH_{max}}
\end{aligned}
\quad (18)
$$

$$
\delta_{DHW_i} \leq 1 \quad (19)
$$

$$\delta_{SH_i} \leq 1 \tag{20}$$

$$\delta_{DHW_i} + \delta_{SH_i} \leq 1 \tag{21}$$

$$Q_{HP_{DHW_i}} \leq \delta_{DHW_i} \cdot \widehat{M}_{DHW} \tag{22}$$

$$Q_{HP_{SH_i}} \leq \delta_{SH_i} \cdot \widehat{M}_{SH} \tag{23}$$

8 Cold delivery

The simultaneous delivery of both heating and cooling led to configurations III, IV and V.

In configuration III, warm combined heating and cooling configuration with warm network, the heat pump had three functioning modes. In the first, the heat pump produced heat, in the second it produced cold, and in the third, the heat pump simultaneously produced heat and cold with no heat exchange with the river. The former two achieved higher efficiencies due to the higher and lower heat source and sink temperatures, respectively. However, the latter exploited the synergies of concurrent production, leading to an overall higher COP.

In configuration IV, classic configuration with warm network and building cold production, the individual heat pumps were independently optimized, in a similar way to the building heat pumps in configuration II. In this configuration, the waste heat of the building chillers was discharged into the district heating network supply pipe, so it becomes available for heat consumers. Afterwards, the district-wide heat pump was optimised with the building waste heat availability in mind.

In configuration V, cold combined heating and cooling configuration with cold network, the algorithm presented in section 7.7 was expanded to take the cold production possibilities into account. In a similar way to configuration III, the heat pump had three operation modes; in the first one, the heat pump solely produced space heating; in the second one, the heat pump delivered domestic hot water; and, in the third mode, the heat pump provided both cooling and domestic hot water.

Configurations III and V were implemented through MILP, whereas LP sufficed for the alternative IV. The details of these programs are provided in the supplementary material.

In the three configurations (III, IV, and V), cold storage was enabled with identical volumetric costs to heat storage, albeit much higher energy cost due to the lower temperature difference. Similarly, heat pump costs were identical to those presented in the foregoing sections for heat production. However, the constant 40-50% Lorenz efficiency was not realistic since it led to remarkably high COP values. Therefore, for the cold production, COP values were approximated according to the formulation presented by Jensen (Jensen et al., 2018), assuming ammonia as refrigerant.

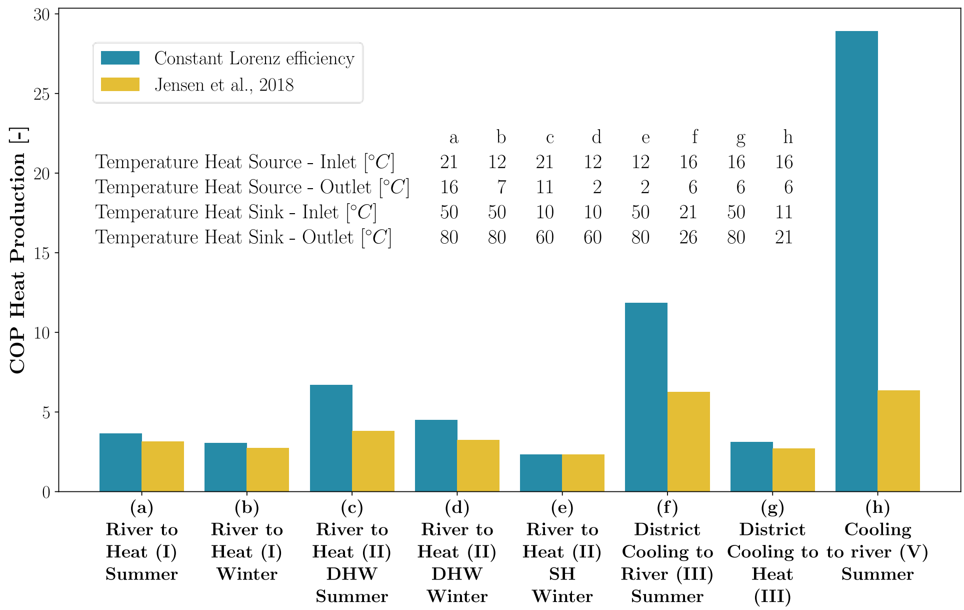

Figure 11. COP for Heat Production under several circumstances[22].

[22] In the Jensen model, the pinch point temperature differences in the heat exchanger were assumed as 5°C and 7°C; the isentropic compression efficiency was taken as 0,75 and 0,7; and

Ammonia was chosen as Jensen et al. only provide model parameters for two refrigerants, ammonia and isobutene. From a practical perspective, carbon dioxide could be a better alternative since it is a natural refrigerant, and it is currently employed for cooling production in small units connected to district heating networks as illustrated by the Danish *Super Supermarkets* project (Adrianto et al., 2018; Funder-Kristensen et al., 2017; Heerup, 2019; Karampour & Sawalha, 2018; Super Supermarkets, 2019)

In Figure 11, the Coefficient of Performance for Heat Production[23] has been plotted for a set of operating conditions using the Jensen formulation and the constant Lorenz efficiency model. As can be appreciated, the constant Lorenz efficiency and Jensen model leads to similar results for heat production either in configurations I or II, although the constant Lorenz efficiency is somewhat optimistic for the determination of COP for Domestic Hot Water production in configuration II. However, the constant Lorenz efficiency significantly overestimates the COP when cooling is produced, and the waste heat is discarded into the river.

9 Administration Costs

The operation of a district heating system not only demands capital and operation expenditures for heat production, distribution and connection to consumers, but it also incurs in outlays for management and administrative personnel, software, consumer relations or auditing as reflected by the Danish District Heating association in its benchmarking statistics (Dansk Fjernvarme, 2013). Since these costs are not included in the other analysed items, they must be added for calculating the total Levelized Cost of Energy.

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the compressor heat loss ratio was supposed to be 0,2 in the district-wide (configurations I and III) and the building heat pumps, respectively.

[23] The Coefficient of Performance for cooling production is one unit lower than the COP for heat production. In some cases, such as g, where both the heat and cold outputs are useful energy, a total COP could be determined equal to twice the heat production COP minus the unity $(2 \cdot COP - 1)$

A 5 €/MWh administrative cost for the district heating solutions was assumed based on the Danish data shown in Figure 12. This value is deemed rather conservative since Spanish unit labour costs are half of the Danish (European Commission, 2023b).

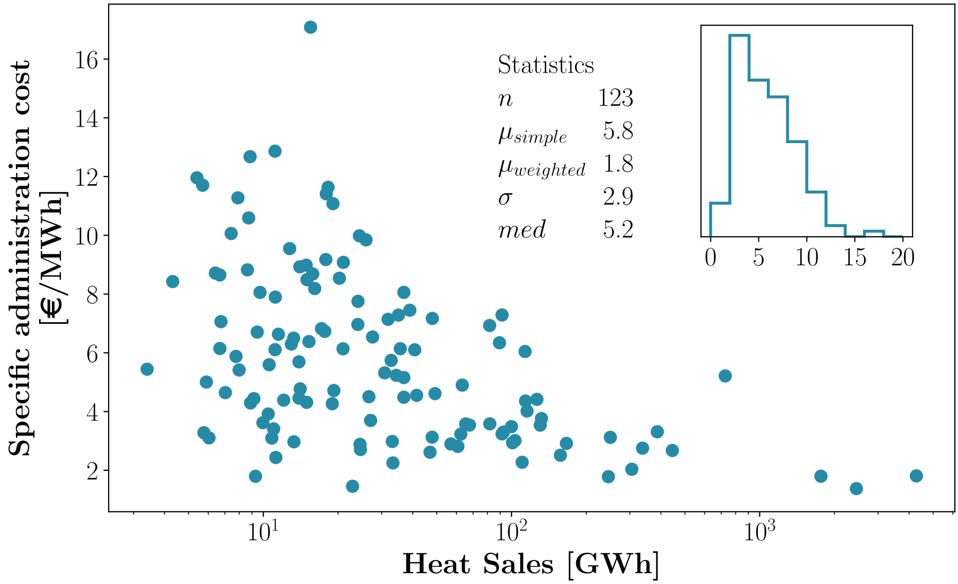

Figure 12. Administration costs in Danish district heating companies. Source: (Dansk Fjernvarme, 2019)

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