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DOI (link to publication from Publisher):
10.54337/aau460188075

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

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BY
NIS BERTELSEN

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

Dissertation submitted: 11th September 2021

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ISSN (online): 2446-1628
ISBN (online): 978-87-7210-989-3

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2021

ENGLISH SUMMARY

This thesis explores heat consumption and planning approaches in Europe through four articles with their main findings summarized and discussed in this thesis. The thesis deploys energy systems knowledge to evaluate the current and historical development of heat supply infrastructures and heat consumption. This is combined with historical and longitudinal case studies exploring successful heat planning attempts and the conditions for enabling them. A review of the energy and climate targets and policies deployed towards 2030 explores the measures the EU-27 countries plan to use to transition their energy systems.

The work is the result of three years occupied with heat planning and consumption from different perspectives. It attempts to combine the techno-economic calculations, energy system models, and strategic plans of energy researchers with perspectives on transitions, change, and implementation of new technologies. The argument is that these approaches needs and can learn from the other. While energy system planners are skilled in calculating optimal system configurations, they lack attention to how their proposals can be adopted in the already existing energy systems of today. Furthermore, there is generally lacking attention to how the specific tools and methods themselves influence their results. On the other hand, these energy system futures are completely central in promoting action and aligning the many different scattered attempts at developing our current infrastructures. Without collective targets and goals, often formulated and circulated in plans, strategies, and policy targets, there would be no concerted actions towards decarbonizing energy consumption.

Heat consumption constitute a significant amount of the total energy consumption in the EU and is therefore central to decarbonize as part of an overall transition to a low-carbon and energy efficient supply. In addition to overall decarbonisation and energy efficiency targets adopted by the EU as well as the member states, there can exist a number of reasons to make changes to current heat supply systems: reducing air pollution, energy security, providing access, energy costs, etc. This illustrates the diverse reasons for interfering with energy supply and engaging in planning efforts. District heating supply is both seen in the academic literature as well as in the EU-27 National Energy and Climate Plans as a central supply system that can participate in future low-carbon energy systems.

The results are based on the four articles making up this thesis. Article 1 investigates the technical and infrastructural conditions of EU heat supply and shows that residential heat consumption is dominated by fossil fuels, primarily in the form of natural gas. While oil and coal consumption for heating has decreased, natural gas consumption has increased. Overall, energy imports are also increasing. CO_2 emissions have decreased since 1990, although if accounting for biomass emissions, total 2015 emissions are still at 1990 levels.

Article 2 draws on the findings in Article 1 and asks how the few countries with high shares of heating supplied through large-scale grid infrastructures, in the form of district heating or gas grid, managed to implement so high shares. This is done by exploring three case studies, the UK, the Netherlands, and Denmark. The results show that developing large-scale infrastructures depend upon coordinating the efforts of multiple, scattered agencies by defining the qualities and purposes of the infrastructures, implementing governance and policy tools that equip actors and ownership models with public engagement. The study show that the developments were not linear developments of simple implementation, but the reasons, drivers, and purposes shifted and emerged through the processes.

Article 3 shifts the focus to a single case study, examining how actors in the Greater Copenhagen district heating system invested and built a thermal energy storage unit. The article examines how plans and strategies informed the work and how actors managed uncertainty the process. The storage shifted qualities and purpose several times throughout the process. The use of the storage was gradually agreed upon through negotiations, deliberations, and using knowledge equipment.

Article 4 resumes focus to the European level and reviews the energy and climate targets and policies deployed by countries in the EU. The results show that the countries have the most ambitious decarbonisation targets for their electricity supply, while heat supply is on level with the overall climate targets. The few countries who have reported specific targets for district heating supply, are all ambitious for the share of renewable energy, indicating the potentials countries see in decarbonizing their district heating supply.

The thesis discuss the results with governance perspectives on how to render rationalities into measurable and discrete objects. The argument is that, in order to steer or govern something, its qualities must be known, discrete, and stable. Drawing upon the Science and Technology Studies literature, the argument that technologies do not have inherent and stable qualities, but that these are rather constructed through the tools and devices used to describe them with, is made. This means that in order to govern new technologies, their qualities must be defined and made stable. Simultaneously, this must convince a long range of actors scattered across different functions and responsibilities in the energy system. Based on this, it is argued that a central challenge for energy and heat governance is to create common understandings and conditions for acting in order to make it possible for actors to implement low-carbon heating solutions.

DANSK RESUME

Denne afhandling analyserer infrastruktur og energiforbrug til opvarmning i Europa gennem fire artikler med hovedresultaterne opsummeret i denne afhandling. Afhandlingen bruger viden om energisystemer til at evaluere den nuværende og historiske udvikling af varmeforsyning og varmeforbrug. Dette kombineres med casestudier af implementering af infrastruktur i tre lande samt en analyse of processen for investering af et varmelager i Storkøbenhavn. En gennemgang af energi- og klimamål mod 2030, udforsker de tiltag som EU-27 landene benytter for at udvikle deres energiforsyning.

Afhandlingen er resultatet af tre års arbejde med varmeplanlægning og -forbrug fra forskellige perspektiver. Afhandlingen kombinerer teknisk forståelse af energiforsyning med perspektiver på implementering. Et centralt argument i denne afhandling er at måden hvorpå en given teknologi bliver beskrevet på påvirker aktørers forståelse og opfattelse af denne. Mens energisystemplanlæggere er dygtige til at beregne optimale systemkonfigurationer, mangler de ofte at være opmærksomme på hvordan deres viden kan informere og indgå i en transitionsproces.

På den anden side er disse planer for fremtidige energisystemer helt centrale for at fremme handling og tilpasse de forskellige spredte forsøg på at udvikle eksisterende infrastruktur. Uden kollektive mål, ofte formuleret i planer og strategier, ville der ikke være nogen kollektiv handling i retning af et lavemissions energiforbrug.

Varmeforbrug udgør en betydelig del af det samlede energiforbrug i EU og er derfor centralt som en del af en samlet overgang til en effektiv energiforsyning baseret på vedvarende energi. Fjernvarme ses som en vigtig forsyningsform, der kan indgå i fremtidige energisystemer. Ud over de overordnede mål for vedvarende energi og energieffektivitet, der er vedtaget af EU såvel som medlemslandene, kan der være en række grunde til at foretage ændringer i de nuværende varmeforsyningssystemer: mindske luftforurening, energisikkerhed, øge og sikre adgang til energi, energiomkostninger osv. Dette illustrerer de forskellige årsager der kan ligge til grund for ønsker om at ændre nuværende forsyningsforhold.

Resultaterne er baseret på de fire artikler, der udgør denne afhandling. Artikel 1 undersøger de tekniske og infrastrukturelle situation for EU-varmeforsyning og viser, at varmeforbruget til boliger domineres af fossile brændstoffer, primært i form af naturgas. Mens olie- og kulforbruget til opvarmning er faldet, er naturgasforbruget steget. Samlet set er import af brændstof også steget. CO_2-udledningen er faldet siden 1990, selvom udledningen af biomasse stadig er på 1990-niveauet.

Artikel 2 bygger på resultaterne i Artikel 1 og undersøger, hvordan de lande med høj andel af varme leveret gennem centrale infrastrukturer i form af fjernvarme eller gas

net, har formået at implementere disse andele. Dette gøres ved hjælp af tre casestudier af England, Holland og Danmark. Resultaterne viser, at udvikling af store infrastrukturer afhænger af at koordinere indsatsen fra flere, spredte aktører ved at definere infrastrukturernes kvaliteter og formål, implementere governance værktøjer, regulering og lovgivning, samt ejerskabsmodeller med offentlig deltagelse. Undersøgelsen viser, at bygge disse infrastrukturer ikke var lineære enkle implementeringer, men årsagerne, drivkræfterne og formålene skiftede og dukkede op under processerne.

Artikel 3 præsenterer et enkelt casestudie som undersøger, hvordan aktører i Storkøbenhavns fjernvarmesystem investerede og byggede et varmelager. Artiklen undersøger, hvordan planer og strategier informerede arbejdet og håndterede den usikkerhed, som aktørerne stod overfor i hele processen. Lageret skiftede formål flere gange gennem hele processen, hvoraf ingen var faste kvaliteter. I stedet blev formålet med lageret gradvist aftalt gennem forhandlinger, overvejelser og brug af viden.

Artikel 4 retter igen fokus på det europæiske niveau og gennemgår de energi- og klimamål og politikker, der er fastsat af landene i EU. Resultaterne viser, at landene er mest ambitiøse med at reducere udledning af drivhusgasser fra deres elforsyning, mens målene for varmeforsyning er på niveau med de overordnede klimamål. De få lande, der har rapporteret om specifikke mål for fjernvarmeforsyning, er alle ambitiøse med andelen af vedvarende energi, hvilket indikerer de potentialer, som landene ser ved omstilling af deres fjernvarmeforsyning.

Afhandlingen diskuterer resultaterne med perspektiver fra litteratur omkring governance. Med udgangspunkt i litteraturen om Science and Technology Studies studier argumenteres der for, at teknologier ikke har universelle og stabile kvaliteter, men at disse snarere konstrueres gennem de værktøjer og enheder, der bruges til at beskrive dem med. Før at en teknologi kan implementeres, investeres i eller bruges skal der etableres enighed om dens kvaliteter. Dette betyder, at for at styre nye teknologier skal deres kvaliteter defineres og gøres stabile. Samtidig skal dette overbevise en lang række aktører spredt over forskellige funktioner og ansvarsområder i energisystemet. Baseret på dette, argumenteres der for, at en central udfordring for energi- og varmeplanlægning er at skabe fælles forståelser og betingelser for at handle for at gøre det muligt for aktører at implementere en varmeforsyning med lav udledning af drivhusgasser.

ACKNOWLEDGEMENTS

I want to start by thanking my two supervisors for this Ph.D. project. Brian did not hesitate when I, as a research assistant at the Sustainable Energy Planning Research Group, asked about the potentials of starting as a Ph.D. fellow. From day one, he trusted me with the responsibility as well as provided the funding for the project. Brian also guided my work, provided important feedback, and was open to most of my strange theoretical and methodological ideas. I am very grateful for the possibility and the journey.

My co-supervisor Peter has since my master's studies been a source of great inspiration and has always been available when I needed help to understand the complex socio-technical relationships we study. When I as a student tried to understand the world ‘out there’ beyond the energy models, Peter provided truly inspiring council that helped me navigate the uncertainties of research. Most of the time, the answer was something along the lines of ‘see what Callon says’, which in fact was, incredibly helpful. As the reader will see, it has influenced and hopefully lifted the results in this thesis. He provided genuine interest in and reflections on my work.

There are many more colleagues I wish to thank. My colleagues in the Sustainable Energy Planning Research Group participated in many fruitful discussions. Four years in this group has given me a solid foundation for understanding energy systems and their complex connections. I am happy to have spent time with energy planners and modellers and I hope that my, at times different viewpoints on energy planning and governance, also have contributed to the group's approach to energy planning.

The ‘Valuation Group’ at AAU gave me a space where I could learn about Science and Technology Studies, Sociology of Markets, Actor Network Theory and how to understand the world ‘out there’. It has both been enlightening as well as a challenge to follow the – for me – high-level and complex sociological discussions.

These two ‘tribes of scholars’ have each contributed to my own knowledge and to how I have approached this Ph.D. project here. I am truly thankful for having spent time in both tribes, and although I am neither a true energy engineer nor sociologist, I still draw upon both schools of thought trying to approach the complex topic of how to both understand and interfere in the world. I believe that one needs both approaches.

To Maëlle I owe special thanks for the support throughout the whole project and for being there when the work was tough. I have been lucky to have a partner who also understands my work. You gave me confidence that this Ph.D. would work out. To my family and friends, thank you for your support through these last years: it has been so important with a life outside of research and to have been able to take my mind off things. Thank you for your interested questions about what I was doing, although I am sure my answers only made you more confused.

Nis Bertelsen

Copenhagen 2021

PEER-REVIEWED ARTICLES

Article 1: N. Bertelsen, B.V. Mathiesen, EU-28 Residential Heat Supply and Consumption: Historical Development and Status, Energies. 13 (2020) 1894. https://doi.org/10.3390/en13081894.

Article 2: N. Bertelsen, S. Paardekooper, B.V. Mathiesen, Implementing large-scale heating infrastructures: experiences from successful planning of district heating and natural gas grids in Denmark, the United Kingdom, and the Netherlands. Energy Efficiency 14 (2021). https://doi.org/https://doi.org/10.1007/s12053-021-09975-8.

First published in Energy Efficiency, volume 14, article number 14, 2021 by Springer Nature

Article 3: N. Bertelsen, M. Caussarieu, U.R. Petersen, P. Karnøe, Energy plans in practice: The making of thermal energy storage in urban Denmark, Energy Res. Soc. Sci. 79 (2021) 102178. https://doi.org/10.1016/j.erss.2021.102178.

Article 4: N. Bertelsen, B.V. Mathiesen, Gaps and ambitions in the goals and policies of the EU-27 National Energy and Climate Plans

Submitted to Energy Policy.

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1 INTRODUCTION

This Ph.D. thesis focuses on attempts to change and steer heat supply. This focus comes from my background as an engineer in renewable energy systems. I became interested in understanding how the actors “out-there” decide on their courses of action. I wanted to participate in mitigating the harmful effects of climate change, but along the way, I became interested in how the actors themselves navigate these uncertain situations. I asked questions about how more knowledge, new energy plans, and strategies would help since I experienced a gap between the knowledge produced and how decision-makers would act upon this knowledge. I realised that it was not simply a question of more knowledge, but also a question of what types of knowledge could contribute to transition processes, sparking an interest in how decision-makers themselves navigate their uncertain situations using knowledge, tools, and methods.

The central subject of this thesis revolves around heat supply and related fuel consumption and enabling technological infrastructure. A significant share of energy consumption in Europe is attributed to heat consumption (Bertelsen and Mathiesen 2020). Residential heating, industry, and services all consume energy for heating, which in 2015 amounted to approximately 50% of Europe’s primary energy consumption, making heat consumption the largest energy end-use, ahead of electricity and transport (Pezzutto et al. 2019). Residential heating in the EU is largely fuelled by fossil fuels, consumed in inefficient stoves and boilers (Bertelsen and Mathiesen 2020). The harmful effects of greenhouse gas emissions on the global climate have been well documented and include global sea level rise, increased temperatures, and more volatile weather (Steffen et al. 2018). The energy transition faces an inherent three-fold challenge; to continuously provide energy services, achieve security of supply and realise greenhouse gas emission reductions (Bale et al. 2015).

Researchers, experts, and modellers are attempting to determine how actors should navigate towards new low-carbon energy supply (Mirakyan and De Guio 2013; H. Lund 2014; Cajot et al. 2017). Making plans and strategies for the development of energy supply is a central part of energy planning practice. We (including myself) try to bring into being new alternatives, technological solutions and debate potential pathways forward. The challenge is that the knowledge produced is not easily transformed into new investments, infrastructure, or technology, nor is it understood in the same by the different stakeholders involved. The gap between plan and realisation seems to be somewhat larger than had been envisioned by many energy engineers and planners.

Social science has made important strides towards highlighting many aspects that have been neglected in energy planning and policy approaches (Sovacool et al. 2015). This work is opening up to the new inputs, opinions, knowledge as well as the technical, social, and economic connections that must be made. I was puzzled by an apparent discrepancy between, on the one hand, how ‘experts’ described the world out-there and advised the many stakeholders on how to navigate it and, on the other hand, the many attempts made by these actors to actually do something about their specific conditions and situations.

Many diverse actors such as energy planners, politicians, utilities, and energy companies are trying to navigate their uncertain, messy realities. They need to maintain energy production to supply consumption while making new investments into future-proof equipment. Energy systems and the responsible actors must deal with the increasing need to decarbonise one step at a time. What are the feasible pathways forward? Who can they collaborate with? What existing equipment is future-proof? There are no simple, right, or straightforward answers to these questions. Instead, stakeholders rely on their knowledge and expertise, the epistemic equipment they use to make sense of these questions, the regulatory and financial situation they must deal with, and the willingness of consumers to use new forms of energy supply, just to name a few factors. Making sense of ambiguous situations involves interpretation, trying things out, and dealing with the results of one's actions (Weick 1995).

These changes are occurring in established large-scale infrastructural systems of energy production and extraction, transmission, and distribution grids connected to the devices of energy consumers (Hughes 1987; Sovacool et al. 2018). It is well documented that existing infrastructure and technologies co-develop with legislation, regulation, user-practices, organisations, and institutions that together maintain and reproduce the role, use, and importance of a technology (Unruh 2000). Using the term socio-technical highlights the conditions and relationships within which technologies exist, and technological change is, therefore, shaped by existing conditions, which in turn shape the deployment of technological solutions (Bolton and Foxon 2015; Edomah et al. 2020). As previously mentioned, there is not one comprehensive socio-technical system, but rather multiple specific interpretations based on the particular perspective of the observer (Jørgensen et al. 2017). Adding to the complexity is the fact that when action is taken by one stakeholder in one direction, it usually produces emergent network effects for other actors. Acting cannot be seen as an isolated event in interconnected energy systems. There is no denying that efforts are collective and interdisciplinary as well as subject to different interpretations.

My aim with this thesis is two-fold. First, I seek to contribute to limiting the harmful use of fossil fuels, inefficient use of energy, and mitigation of climate change. I aim to do this by describing historical and current developments in heat supply as well as by examining how changes have previously been made. Knowledge about the current state of heat supply and planning attempts can hopefully contribute to new action towards a decarbonised heat supply. Second, I wish to increase the reflexivity of the work of engineers, modellers, and researchers who produce plans, strategies, feasibility studies, etc. These two aims are inherently intertwined in a complex way. As I show throughout this thesis, knowledge generation is completely crucial to promoting change. However, knowledge generation is not an exercise that objectively uncovers facts about reality, instead it successively brings it into being in ways that can enable actors to engage with the messiness of reality. My approach seeks to outline the importance of establishing stable knowledge configurations to facilitate actors' decision-making in situations of uncertainty.

This thesis presents the results and reflections of my Ph.D. research from 2018 to 2021. The main research is published in four articles, which are available in the appendix. These articles approach heat supply from four different perspectives, each contributing to an analysis of how changes in heat supply have occurred historically, what the current situation in the EU looks like and how the different countries aim to go forward. The thesis itself is a summary and presentation of the results, but it also builds on this work and attempts to theoretically advance the discussion on heat planning and generalise some of the findings and arguments beyond the point reached in the articles.

1.1 THE CHALLENGE OF DECARBONISING HEAT SUPPLY

Heat supply is, as I demonstrate in this thesis, not a single, stable connected system. Instead, it is composed of different configurations of buildings, boilers, fuels, users, and suppliers to name just a few of the elements. Heating is not a single object but is often scattered between fuel policies, the building stock and energy efficiency improvements, often governed by municipalities without central coordination from governments or ministries (Webb et al. 2016). The technologies used, the infrastructure they depend on and the fuels used also vary widely from country to country. Heating is, therefore, an important energy end-use due to its significant energy consumption, but it also depends on the actions of many scattered actors in order to change the status quo.

Major international institutions (UNFCCC 2016; European Commission 2019a; European Commission 2019b), city governments (Kern and Bulkeley 2009), companies, and citizens are committing to mitigating the effects of climate change. While these global challenges are of great importance, there are multiple other reasons for engaging with the current energy supply and wishing to change it. In addition to driving climate change, heat consumption is a major contributor to air pollution (Bulkeley and Betsill 2013; Sovacool and Martiskainen 2020). Furthermore, other issues include energy security and imports (Goldthau and Sitter 2015; Prontera 2020), energy justice, and access (Butler et al. 2018; Jasanoff 2018). This leads to a central aspect of this thesis; while climate change is becoming an established fact that engages stakeholders in a struggle to decarbonise energy supply, they do this from their own particular positions. While a phenomenon such as carbon emissions are well described in terms of effects on the global climate, the specific strategies, actions, and navigations taken by the actors who are faced with investment, policy, and operational decisions emerge from the socio-technical configurations within which they operate.

Heat supply and consumption are shaped by the specific socio-technical situations, resulting in different conditions and contexts all over Europe. No situation is the same, but all they depend on the specific local conditions shaped by infrastructure, technologies, expertise, knowledge, citizens, habits, regulations, financing and many more factors. These are open-ended, continuous processes in which actors and stakeholders attempt to navigate uncertain situations towards unknown futures, while ensuring that their existing infrastructure is useful and relevant (Caussarieu 2021). The reasons for changing current heat supply are as diverse as there are actors conducting heat planning.

District heating systems have been highlighted for their potential to decarbonise energy supply. It has been argued that they exploit otherwise wasted energy from energy processes (Rasmus Lund and Mathiesen 2015; Mathiesen et al. 2015), provide access to heat sources such as geothermal, large-scale heat pumps, or solar thermal (David et al. 2017), the utilisation of which is unfeasible on the scale of a single building and potentially increase energy system flexibility by connecting sectors (Kirkerud et al. 2017; Arabzadeh et al. 2019). While some newer technological concepts such as low-temperature supply (H. Lund, Werner, et al. 2014) still require technical innovation, district heating is a well-established technology, especially in the Scandinavian countries (Bertelsen and Mathiesen 2020). While research has shown that from a socio-economic perspective, increasing district heating supply to around 50% of EU heat demand would be cost-effective and would support the decarbonisation of energy supply (Connolly et al. 2015; Paardekooper et al. 2018), these findings have yet to manifest themselves in investments across the countries in the EU, and the share of district heating in residential heat consumption has not increased since (Bertelsen and Mathiesen 2020). The implementation of large-scale grid infrastructure, characterised by high initial investments and long lifetimes seems to be facing challenges outside the few countries that today have district heating. It seems like new approaches, understandings, and governance for heat supply and district heating systems are needed.

1.2 PROMOTING CHANGE AND POTENTIAL TECHNICAL SOLUTIONS

One approach in the energy planning literature that describes how to promote technological changes is called *Choice Awareness* (H. Lund 2014). I turn to the Choice Awareness theory here because it highlights the role of new knowledge in energy planning. Scholars of Choice Awareness argue that the technological choices that are accepted at the societal level are shaped and influenced by the interests and habits of established organisations and institutions. Incumbent actors will attempt to eliminate knowledge about alternatives to established fossil fuel technologies as feasible technological pathways, through direct or indirect interference by actors deciding which alternatives should be included in assessments, or by influencing perceptions, habits, values, and norms. Rendering novel technologies relevant involves increasing *Choice Awareness* about them through new methodologies, feasibility studies, and by using new expertise and tools that assess renewable technologies based on their role in future low-carbon energy systems rather than in existing fossil fuel systems (H. Lund 2014).

However, it seems that the Choice Awareness approach skips a step as it does not outline how or why such new alternative ways of knowing become accepted or fail. It is implicitly understood that calculative demonstrations showing renewable energy as a cheaper, better, or more efficient alternative will result in the materialisation of these technologies. However, as I argue in this thesis, such representations of technologies are always partial framings that highlight specific qualities of technologies while obscuring others (Callon 1998; Çalişkan and Callon 2010). A description of the qualities or potential of a technology also needs to be relevant and interesting for the users, receivers, or public who are the focus of such awareness raising. Therefore, the specific ways that renewable energy is *made known* to actors is of paramount importance. This highlights a central tenet of this thesis: the ways in which socio-technical objects are made known do not objectively bring the objects true qualities out into the open, but instead represent specific, partial ways of describing certain aspects of the objects in question while obscuring others.

The ways in which heat planners make sense of ambiguous situations may very well influence whether district heating is deemed a viable or unfeasible type of supply. For example, using a high rate of return or a short investment horizon will, in many cases, mean that the investment in district heating infrastructure will not be feasible due to its high initial costs and long lifetime. Experience with corruption or poorly performing public sectors may have an influence on how collective heat supply is perceived. Furthermore, how should municipal heat planners handle the different arguments of lobbyists and experts advising on energy efficiency and near-zero energy buildings, electrification of heat supply, or district heating (see, for example, Späth and Rohracher 2015)? Providing Choice Awareness by conducting analyses and highlighting potential benefits is an important part of creating change and outlining potential pathways forward. However, simply creating new and more knowledge may not be sufficient: the knowledge has to interest someone, convince them to take action, describe how they themselves can participate in the energy transition, and help actors navigate uncertainty.

1.3 GOVERNANCE FOR HEAT PLANNING AND TRANSITIONS

How do actors navigate their situations, take decisions, steer and control their equipment, infrastructure, and supply systems, objects that are often diffuse and not readily available to be engaged with? I define governance as the diverse attempts to come to know, engage with and plan changes and maintain existing and future systems (Miller and Rose 2008). District heating grids are buried underground, end-users and their heating equipment are scattered within multiple buildings in a supply area, and several producers may be responsible for coordinating their energy deliveries to meet demand. Heat supply systems are not discrete objects that are just ‘there’: they require tools, expertise, and knowledge to make them known to the interested parties. This understanding inherently ties governing together with the ways objects are made known. A few examples are beneficial, and I here draw on literature outside the energy field. Piketty (2014) shows how most of the initial attempts to measure land value, stock of capital, and national income were for tax purposes. Without knowing who owned what and how much, taxation was simply not possible. In the field of medicine, the categorisation of diseases enabled doctors to share research and experience and teach as they could refer to the same definitions of illnesses, which provided a sort of framework for communication (Bowker and Star 1999). Another example is measuring and classifying forests and their trees in order to estimate logging output (Scott 1998). Without coming to know these diverse subjects and objects through specific tools, calculations, classification, and expertise, they could not be mobilised, engaged with, or used. Knowledge production is central to governance.

Technological transitions and the implementation of new technology, therefore, depend on knowledge creation and circulation. However, simply increasing knowledge is insufficient as it is important to consider how this knowledge is created and which particular qualities of a technology it highlights (Miller and Rose 2008). Technological potential also depends on the specific socio-technical situation technologies are to be placed within (Unruh 2002). Existing infrastructure and supply systems, knowledge and expertise of planners, policy makers, and system users as well as regulations and legislation are all factors that also shape the conditions into which new technology must be implemented (Callon 1991; Unruh 2000). Planning and governance of low-carbon heating transitions is not simply a technological task as it must deal with all the complexity and messiness of the world ‘out there’. New technologies are implemented into already existing systems and must work given established market conditions, regulatory frameworks, user preferences, and expert knowledge (Unruh 2000). Therefore, it is important to examine and understand the specific conditions and their historical development as they shape the situations into which new technologies are to be implemented.

Therefore, the governance and planning of heat transitions involves creating Choice Awareness, but the way in which these alternatives are made and brought into being must also be carefully considered. Such alternatives must be made in ways that are interesting and useful for other actors. The usefulness of such accounts may include highlighting potential paths of development, exploring different options, or answering questions about uncertain situations. Planning and governance for a low-carbon heat supply is driven by the making and production of knowledge and claims about reality and, therefore, actors must consider how such knowledge is used to steer transitions. A transition does not simply involve a linear development from plans to technology as the process is uncertain and messy with shifting understandings of reality and it depends on historical contextual situations. Consequently, this should be actively considered in low-carbon heat governance.

1.4 RESEARCH QUESTION

While this Ph.D. project has its roots in a technical planning approach, I set out to investigate how certain engineering concepts became reality, which governance approaches were necessary for implementing novel cross-sectoral energy systems and which actors were involved, and what kinds of business models, regulatory tools and planning methods were used. The knowledge gap I address in my research relates to identifying which governance approaches are useful in order to achieve new cross-sectoral integrated investments for realising decarbonised energy systems. This I have examined in the four articles that comprise this thesis.

The approach combines technical knowledge of how energy systems can be configured to achieve decarbonisation in a cost-effective manner with a rejection of the assumption that energy planners, policy makers, and decision-makers can objectively manage the energy transition from a distant and privileged position. The thesis thus explores the following question:

> What are the current and historical conditions of EU´s heat supply and how can heat planning and governance help planners and policy makers to navigate uncertainty towards a low-carbon heating future?

The EU is understood both as the organisation, the European Union, but also the individual countries that comprise the union. This geographical scope was chosen as the countries, despite having different conditions, still adhere to the climate policies of the European Union. This meant that these countries, who are obliged to act according to the EU’s climate targets and adopt the Paris Agreement (European Commission 2019c; European Commission 2019b), could be studied and compared. It also presents an interesting case of how heat supply, so often argued to be situated and governed locally, is approached by the EU as well as national governments. The withdrawal of the United Kingdom from the EU, a process commonly known as Brexit, which commenced with the referendum of June 2016 and was effectuated in January 2020, means that the UK formed part of the initial analyses in this thesis, but it became necessary to exclude the UK from my subsequent analyses once the country was excluded from EU-wide datasets. When results apply to the countries of the EU as well as the UK, I designate this the EU-27+UK.

Heat supply is here understood as encompassing the fuels, energy carriers, technologies, and infrastructure used to supply heat demand, as well as the physical environment including the building stock. In addition to the technical side, heat supply also comprises regulations, habits, expertise, and know-how. These factors form part of what I term the current and historical conditions.

Heat planning and governance includes the diverse attempts to know, shape, steer and control heat supply. Many different actors conduct planning and governance and none are in a privileged position whereby they can dictate a specific outcome. The term navigate, therefore, becomes central as diverse actors attempt to navigate the heat supply conditions to achieve a low-carbon heating transition. Transitions are implemented one step at a time, each of which entails navigation choices. Furthermore, as heat and energy systems become increasingly complex and interconnected, the need to coordinate progress and action among actors increases. Within the overall goal of moving towards a low-carbon society, there can be found many diverse targets, agendas, and aims as well as significant uncertainty on the pathway forward. Although significant resources are being mobilised to decarbonise energy supply, the final outcome of this huge task remains unknown, and it can materialise in a number of different ways. Therefore, the research question asks how planning and governance can help planners and policy makers to navigate this uncertainty.

1.5 STRUCTURE OF THE THESIS

The thesis is structured as follows: First, chapter 2 presents the main theoretical arguments and positions of this thesis. The chapter discusses how governance inherently relies on knowledge creation and how knowledge claims about objects are always partial framings rather than holistic objective truths. The theoretical discussions progress to investigate the implications of this for attempts to govern and steer technological development. Chapter 3 discusses the methodological choices and concerns of this thesis and presents how the four articles that make up this thesis each contribute with their findings. Chapter 4 presents the literature on potential technological solutions, and among other technologies, discusses the role of district heating systems for heat supply in a decarbonised energy system. The chapter seeks to identify some of the main implications of these technological choices in terms of implementation, regulation, and governance. Chapter 5 presents and critically analyses some of the main arguments on energy planning from the academic literature. Central in the literature are approaches that focus on *local* planning and advocate *holistic* knowledge production in order to come to know the research object. Based on the main findings from Article 1 and Article 4, Chapter 6 presents an account of the current and historical conditions of heat supply in the EU-27+UK countries. This forms the basis of a discussion of the different situations the various countries are in based on their current heat supply infrastructure and systems. Chapter 7 presents the main findings from Articles 2 and 3 form the basis of a discussion of how large-scale infrastructure for heat supply in Denmark, the UK, and the Netherlands was implemented. The chapter continues to elaborate on a case of how actors in Greater Copenhagen managed uncertainty during the investment process of a thermal energy storage unit. This section elaborates on how heat planning can be seen as a loose assemblage of scattered agents, who still manage to coordinate their work by following regulations, strategies and engaging with collectively understood challenges. Finally, the main conclusions of this thesis are presented in Chapter 8, which summarises the current state of heat supply in the EU and how governance, planning, and regulation can contribute to decarbonising heat supply.

2 KNOWLEDGE ASSEMBLAGES FOR GOVERNING HEAT TRANSITIONS

Knowledge creation has always been closely connected to governing. Scott (1998) shows how important implementing the metric system was in establishing the French State during the French Revolution. New measures such as the *metre* and the *kilogram* facilitated trade by introducing legible standards and made centralised administration possible as statistics could be collected more easily. As the revolutionary decree stated, "*The centuries old dream of the masses of only one just measure has come true! The revolution has given the people the meter!*" (Poggi 1978, cited in Scott 1998, 32). However, such epistemic governance devices are not implemented easily. Despite the decree of confiscating *toise*[1] sticks and exchanging them with metre sticks, the French population continued using the toise as an everyday measure for decades (Scott 1998). This example highlights the content of the following theoretical discussion: first, before a subject or socio-technical object can be steered or governed, its qualities, properties and effects must be known. Second, the way these qualities are known depends on the specific tools, standards and measurements used. Last but not least, the adoption of new ways of knowing and governing is not an easy task as it relies on changing the habits and increasing the expertise and knowledge of the diverse actors who engage in the epistemic processes.

Recent governance approaches highlight the role and production of knowledge as a central component in steering uncertain, emergent processes of energy system transitions (Voß and Freeman 2016). Epistemic governance moves away from the understanding of knowledge production as passively mirroring reality towards actively participating in making it visible, thereby rendering reality amenable for intervention (Miller and Rose 2008). Moving from hierarchical and centralised *government* of the nation state to dispersed sets of networked actors engaged in relational *governance* relies increasingly on the production, circulation, management, deployment and use of knowledge (Voß and Freeman 2016). This also highlights the role of epistemic devices such as the tools, methods and calculations that are central in governing, measuring, tracking and aligning progress, action and the everyday work from public officials to citizens and companies:

> "It draws attention to the fundamental role that knowledges play in rendering aspects of existence thinkable and calculable, and amenable to deliberated and planful initiatives: a complex intellectual labour involving not only the invention of new forms of thought, but also the invention of novel procedures of documentation, computation and evaluation" (Miller and Rose 1990, 3).

[1] The metre was defined as 1/10.000.000 of the distance from the North Pole to the Equator. A toise was approximately 1,949mm.

Miller and Rose (1990) point out two important factors. First, the importance knowledge plays in making action possible in uncertain situations. To be able to deliver on political rationalities and discourses, they must be rendered countable, manageable, known and discrete. Second, novel ways of collecting, documenting and calculating knowledge are necessary for new modes of governance.

A few examples highlight the necessity of making the subjects of governance attempts countable. In order to govern the amount of fish that sailors are allowed to catch, Individual Transferable Quotas (ITQs) are used to designate the amount each boat is allowed to catch. Holm and Nolde Nielsen (2007) describe how ITQs came into existence through complex modeling technique, *Virtual Population Analysis*, which estimates the total number of fish and the consequences fishing will have for the current stock. Only once a reliable estimate of the fish stock size had been made, did it become possible to introduce ITQs and govern the sailors and the amount of fishing (Holm and Nolde Nielsen 2007). As *"fish are hard to count"* (Holm and Nolde Nielsen 2007, 180), it can be argued that the ITQs and their governance naturally relied on estimates using analytical equipment. Garcia-Parpet (2007) provides a similar example in her study of the establishment of a strawberry market in France: the market relied on measuring and weighing the strawberries, classifying them in different qualities and introducing guarantees of origin. All these measures allowed the quality of the strawberries to be determined and a price to be set, which facilitated exchange. The literature on Science and Technology Studies has fruitfully investigated this topic in diverse settings such as infrastructure (Winner 1980) and laboratories (Latour and Woolgar 1987). A central tenet is that objects do not inherently contain meaning that can be made known, i.e., an objective reality, but instead they are subject to the situated understandings of particular actors (Bijker et al. 1987).

2.1 FRAMINGS AND TECHNOLOGICAL QUALITIES

As discussed in 1, the Choice Awareness concept (H. Lund 2014) stresses the importance of creating new knowledge about alternative solutions in order to promote change. If there is no knowledge about alternatives, how can actors act differently? This is also a central tenet of Callon's (1995) account of scientific progress. Callon describes how the US nuclear programme during World War II hinged on Einstein convincing Roosevelt about the importance of the research and development of the nuclear bomb: the actor *Roosevelt-who-wants-the-bomb* became interested through the physics descriptions of the potential bomb. However, here there is a crucial difference between the Choice Awareness concept and Callon's argument: changing an actor's viewpoint by showcasing the potential of alternatives depends on the actor's *interest*. If a description of an alternative technology does not satisfy the wishes, obligations or practical needs of an actor, then it is not much use. Isabelle Stengers puts it this way:

> "To interest someone in something means, first and above all, to act in such a way that this thing – apparatus, argument, or hypothesis … - can concern the person, intervene in his or her life, and eventually transform it" (Stengers, quoted in Law 2004, 39).

Therefore, changes to socio-technical systems rely on making them known in ways that interest others and render them accessible to intervention by governance actors. Consequently, it is useful to discuss how and under what conditions stable facts and statements about socio-technical objects emerge, circulate and are used. A description of technologies and their qualities, uses and potential is often included in documents or outlined in plans. Such future plans, strategies and scenarios have been called *socio-technical imaginaries* (Jasanoff and Kim 2009). These visions both prescribe and describe attainable futures by collectively imagining technological and social developments and the goals needed to reach them.

Ways of presenting technologies and other socio-technical objects do not neutrally mirror a reality, but are instead used to project certain aspects while hiding others (Latour 1999). A company's business model and value proposition is one example of such an empirical device. Doganova and Eyquem-Renault (2009) argue that business models do not make objective descriptions of a company's real situation or economic conditions. Instead, they present a company from a specific perspective to highlight certain aspects and key figures, which makes the company attractive to investors and allows the presentation of the company to be circulated among actors (Doganova and Eyquem-Renault 2009).

The specific ways in which objects are measured produce meaning and understandings about those particular objects. These can be categories, or they can involve the way in which objects are quantitatively measured:

> "Making measures is a way of making meaning and, concurrently, of making meaning visible. In this sense, the relationship between measure, value and visibility is intrinsic: if we aim to measure something it is because we deem that something, albeit existing at a 'latent' stage, to be of some relevance to us." (Brighenti 2018, 28)

Such analyses rely on metrological tools to produce data about their objects of inquiry, algorithms and formulas to process data and expertise to interpret the results.

A particular arrangement of heterogeneous actors is necessary in order to produce usable framings about the objects of inquiry (Çalişkan and Callon 2010). The concept of *framings* refers to the specific ways technology (or other objects) are characterised and their effects qualified (Callon 1998). By using the word framing, attention is focused on the specific perspective of the viewer and the qualities that are inside and outside the frame. Nuclear energy provides an example of different, often competing framings, as the technology is often presented as *safe*, *cheap, necessary* or *expensive*, all depending on the metrics used in bringing out the qualities, e.g., which are included and which are excluded (Garud et al. 2010). Framings depend on establishing a knowledge infrastructure that simultaneously reduces the amount of information about a subject while amplifying the remaining data that is used to describe the properties of the objects (Latour 1999). Only by excluding certain aspects can others be brought forward. Framings are the result of established, agreed upon understandings of what counts and what does not. More specifically, concerning models, tools, methodologies and expertise, we can say that they always reduce complexity in order to say something useful about the object in question:

> "We cannot deal with reality in all its complexity. Our models have to reduce this complexity in order to generate some understanding. In the process, something is obviously lost. If we have a good model, we would hope that that which is left out is unimportant" (Cilliers 2001, 137).

While framings represent an attempt to decide what should be included in understandings of a specific technology, they can be difficult to sustain. Often they *overflow* with effects that cannot be contained by the framing (Callon 1998). Callon (1998) argues that instead of overflows being rare, they are the norm and stable framings are costly to establish and difficult to maintain. The nuclear energy example illustrates how overflows often occur. The Fukushima accident overflowed the *safe* framing and prompted several countries to make changes to their nuclear supply. New nuclear technological developments framed their technologies as *safe* as well as a *stable source* of CO_2 emissions free electricity (see, for example, Seaborg 2021). This highlights that technology is described, qualified and framed in specific ways, often with the aim of convincing actors or organisations. This effort to interest and convince must be carefully maintained in the face of changing perceptions.

While much research is focused on defining and qualifying objects, Stirling (2005) argues that the process of evaluating technology can essentially serve to *open up* for new qualifications and re-framings or *close them down* by settling contested understandings, deciding on particular framings and managing overflows. Processes of opening up can also arise from overflows of established framings, thereby engaging actors and their epistemic devices in trying to close down the framings not contained in established understandings.

2.2 SOCIO-TECHNICAL ASSEMBLAGES

Several academic accounts and research strands investigate how technology co-develops in society and how it is not possible to separate technological artefacts from their ties to society (see, for example, Geels 2002; Bijker et al. 1987; Garud and Gehman 2012). Unruh (2000, 2002) examines how *Techno-Institutional Complexes* (TICs) form through increasing returns to scale and the co-development of technological, organisational, industrial, societal and institutional factors lock in certain types of technologies through path-dependent development. Hughes (1987) investigated how large-scale infrastructural systems were built and found that the physical infrastructure was developed alongside legal, regulatory, knowledge and user involvement.

These perspectives provide valuable explanations for how technological innovation occurs and how both barriers and opportunities around the technological artefacts shape the development. The authors behind many of these approaches talk about transitions or technologies using terms such as systems, networks or regimes (Unruh 2000; Geels 2002; Geels and Schot 2007). Such approaches have received criticism for not accounting for the messiness of actor-realities as well as for promoting a structuralist ontology that overly relies on pre-existing categories (Iuel-Stissing et al. 2020; Caussarieu 2021). Therefore, in the following, I present the notion of a *socio-technical assemblage* (Çalişkan and Callon 2010). While sharing some similarities with the abovementioned approaches, the term assemblage highlights a more fluid, less stable and ever-changing configuration of socio-technical actors and devices that together make up the assemblage. An assemblage is made up of heterogeneous elements and actors depending on the specific situation. Central to this approach are the *devices* that calculate, define and specify properties (Callon et al. 2007). The role of devices has already been highlighted by Miller and Rose (2008) above, but they increase in importance when understood as part of an assemblage. *"They articulate action, they act and make others act"* (Callon et al. 2007, 2), but they also highlight the intrinsic relationship between the device and their user. There is always an operator, analyst or user who deploys the epistemic device and interprets the results. The notion of assemblage also limits the differentiation between local and global factors and instead points to the specific connections in a situation that enable and constitute the assemblage[2] (Latour 2005). All acting happens *locally* in the specific situation, but at the same time produces effects that affect all connections in the assemblage.

Jensen et al. (2015) argue that specific framings are established and rendered useful through, "*distributed and generative struggles and alliances that play out among fractured and partly incomplete sociomaterial assemblages of the urban context, rather than as a series of fortified mechanisms*" (Jensen et al. 2015, 557). Instead of highlighting how socio-technical regimes or TICs develop following fixed and rigid societal structures, using the term assemblage focuses on how stable socio-technical configurations and framings are established and maintained in messy and uncertain situations.

The above discussion illustrates that there is no shared system logic, but instead scattered agency among different stakeholders, each of whom appreciates the socio-

[2] Throughout Actor-Network Theory and the Science and Technology Studies literature, terms such as network, assemblage, agencement, arrangement are used to highlight the connection between heterogeneous actors and elements.

technical system from their particular vantage point (Iuel-Stissing et al. 2020). Epistemic devices here allow actors to render the socio-technical systems visible, tangible and actionable, but these devices are often specifically made-for-purpose by the actors and, therefore, produce particular accounts and not shared or common system understandings.

2.3 GOVERNING AT A DISTANCE

The term assemblage points to the specific epistemic devices such as the tools, methods and statistics that assemble and maintain certain framings of technological objects. As previously mentioned, these epistemic devices are central to being able to govern, steer and control. However, such governance does not occur through form of direct control, instead it has been labelled *Governance at a Distance* (Miller and Rose 2008). Epistemic devices participate in rendering governance and policy rationalities operable by diverse independent actors. By equipping actors with tools to measure, collect statistics and navigate uncertainty, their action can be shaped in similar directions:

> "Government here works by installing what one might term a calculative technology in the heart of the "private" sphere, producing new ways of rendering economic activity into thought, conferring new visibilities upon the components of profit and loss, embedding new methods of calculation and hence linking private decisions and public objectives in a new way – through the medium of knowledge" (Miller and Rose 2008, 67).

Instead of directly interfering with decision-making, governing at a distance represents an attempt to steer and guide by making specific things and qualities known. Examples include hospitals tasked with translating their activities from laundry, operations and therapy into cash equivalents (Miller and Rose 2008) or the Danish socio-economic calculations of district heating projects (Karnøe and Jensen 2016). Installing these governance devices does not necessarily result in the desired outcomes. Actors sometimes interpret the use and outcomes differently, they are deployed for the users' own benefit, they lack the specific conditions that make them work such as reliable statistics and data or suffer from a lack of communication:

> "We do not live in a governed world so much as a world traversed by the 'will to govern', fuelled by the constant registration of 'failure', the discrepancy between ambition and outcome, and the constant injuction to do better next time" (Miller and Rose 2008, 71).

Latour (1994) provides a simple example of how an assemblage configures and shapes action at a distance with his description of how different devices, knowledge and habits enable mundane activities – in this case driving. Traffic safety is achieved through several different elements and devices such as knowledge of and training in traffic regulation, the expertise learned when taking the driver's test, road rules and design and traffic signs. A speed bump is a simple technology that is utilised to remind drivers to slow down in specific situations, where their training and road signs are not effective. However, such assemblages are not perfect: it is necessary for the driver to interpret road conditions, remember road signs and rules or adapt to local habits if driving in new areas. Accidents are frequent when drivers do not follow rules or lose concentration.

What does driving have to do with heat supply planning and governance? The example highlights the same loose and fluid assemblage that sometimes renders heating amenable to intervention but also often fails to produce the desired effects. Driving is governed by road signs, speed bumps, learning, police checks and legislation that penalises offenders. Heat planning can be understood as a similar assemblage encompassing fuels, supply, energy efficiency, air pollution, expertise and training, market rules and regulations, building codes and access to finance to name just a few. These factors combine to deliver the conditions for conducting heat planning, but they do not represent a fool-proof *system* or *regime* that never fails. Sometimes, under some conditions and in some places, heat planning works well while it does not in others. The outcomes are emergent based on the specific conditions.

In the driving example above, the whole assemblage is local: the speedbump, traffic signs, the drivers training and knowledge, etc. In order to act globally, one can delegate responsibilities to technologies, objects, regulation or legislation (Johnson 1988), but these are always applied in the local conditions. Just as heating and energy legislation, regardless of how national or global its focus, will always be interpreted locally by the specific user and given the specific conditions (Latour 2005). *Governing at a Distance* highlights this perspective: that in order to act on or with someone or something, an assemblage must render the action operable (Miller and Rose 2008). The crucial perspective is that attempts to act globally, such as writing laws and regulation, will always be interpreted, deployed and used in a local situation, thus opening up for different interpretations, uses and outcomes. It also highlights that such authoritative attempts to govern and steer by, e.g. imposing mandatory use of epistemic devices, rarely work alone but instead contribute to the governance assemblages (Brighenti 2018; Iuel-Stissing et al. 2020). A single regulation or policy may not stimulate much action, but when it interacts with a plethora of legislation, epistemic devices, potential futures, interests and agendas of actors, business cases and available finance, such assemblages may provide agency for the scattered actors and stakeholders.

2.4 STABLE KNOWLEDGE FRAMINGS TO PROMOTE CHANGE

Combining the knowledge governance of Miller and Rose (2008) with attention to the specific assemblages and knowledge devices (Callon et al. 2007) highlights how particular assemblages render technologies and objects visible, discrete and governable (Cashmore et al. 2019). The notion that socio-technical objects are always known through particular framings and never in their entirety does not solve the problem of how to create agreement and facilitate collective work among actors. Instead, it illustrates the difficulties actors face in creating agreements and stable common understandings. However, taking this approach also reveals important new understandings for the governance task of facilitating communication across diverse actors by assembling stable frameworks enabling action towards low-carbon energy systems. An approach that simply entails *more* knowledge production will not necessarily facilitate reaching common understandings as knowing socio-technical objects will always happen through partial framings. Acknowledging the fundamental difficulty of knowing an object in its entirety instead highlights *how* different actors come to know their objects, and perhaps more importantly, how governance attempts can attempt to create *common* understandings:

> “The key political question for an ontological politics of urban assemblages is not first and foremost for whom these function, but rather how shared urban realities are made and remade in various contested practices” (Farías and Blok 2016, 7).

While Farías and Blok (2016) take an urban focus, the argument is also valid for energy planning. As previously argued, energy is intertwined in many different assemblages and, as we will see later, authors within the field of energy planning are increasingly arguing for energy transitions to be taken up by urban actors.

While I have argued above that knowing the object to be governed will always involve a particular framing assembled through expertise, regulations, tools and devices, the *objective* of governance processes is often to establish the governance object as a discrete and known object with stable qualities (Smith and Stirling 2007). Only when the framings are stable, accepted by actors and widely used without overflowing are they useful for governing objects. Smith and Stirling (2007) propose two models for understanding governance processes. First, *governance on the outside* attains an objective distance to the discrete knowable object to be governed. From this position, governing agents are able to make the object known, produce agreements among the involved stakeholders and, from this basis, objectively intervene and steer the process in the desired direction. From the privileged outside position, the system boundaries can be known and agreed upon. While this model recognises that several stakeholders with potentially conflicting objectives are present, it is still assumed that knowledge production will result in similar understandings of the object. Since it is “out there”, making it known will identify its properties, which will inform governance outputs and “optimal” options. By broadening the inputs into this model, more aspects will be included in the knowledge generation, thereby providing a clearer, more complete picture.

Smith and Stirling (2007) label the second ideal type of governance process *governance on the inside.* The governance agents and their attempts to make the governance objects are not objectively outside the governance process but are instead situated within. The governance arena and the socio-technical system it seeks to govern are part of the same network. Also, as the governance object is no longer external to the governance process, it cannot be made known in its entirety. Instead, governance actors will all have their own, possibly incommensurable, framings of the situation. Several different understandings, perspectives and knowledges simultaneously exist and are all equally valid ontologies. The consequence of a *governance on the inside* perspective is, thus, that there is no privileged knowledge position or final reality or truth about the technology that will be discovered through epistemic work. More knowledge production will simply reproduce already existing actor positions. Therefore, agreements and closure are not only reached through knowledge production, but through negotiations and deliberation.

Neither of the two ideal types are ever reached in practice. While governance actors cannot escape being part of the assemblages they try to govern, it is precisely the establishment of this sense of *outside* position that enables socio-technical objects to be governed, mediated and engaged with. A true *outside* objective understanding of a socio-technical object will also never be reached as stakeholders and actors will always interact with the systems from their particular situations. However, it is possible to establish some shared understandings of system development, future pathways or objectives. For example, the need to shift away from fossil fuels is becoming an accepted and shared goal for many energy system actors, just as increasing energy efficiency and shifting away from oil supply was a widely accepted goal among Danish energy system actors in the 1980s (Rüdiger 2014; Rüdiger 2019). It also seems that solutions such increasing the flexibility of the electricity system are accepted among stakeholders, although how this should be achieved is still contested (Iuel-Stissing et al. 2020). We can thus say that although an outside position will never truly be reached, establishing stable framings of socio-technical objects, which allows them to be seen as discretely, knowable objects, also promotes common responses from scattered actors and facilitates the governance of these objects. The struggle for new governance processes will be to establish new stable ways of knowing and engaging with the objects in question.

Governance assemblages

This section has introduced several concepts from the literature on governance and from Science and Technology Studies. The notion of assemblage describes the heterogeneous actors and elements that together assemble and enable agency. They are not fixed networks with predictable outcomes, instead the results are emergent, uncertain and often subject to change. This term also highlights what is for much of the energy planning literature, as I demonstrate below in 2, a new understanding of what *local* means. All acting is local, and everything is situated in the particular conditions. This means that while regulation, legislation and other mandatory requirements might apply nationally to all actors, these elements are still interpreted and enacted *locally* in their particular assemblages. The term *governance at a distance* highlights this and also points to the specific devices that enable governance and steering in particular situations. A tool, device, regulation or requirement has to be made useable, rendering something measurable and knowable. Just as in the driving example above in which traffic signs and speed bumps work in the particular situation, calculation rules, specific knowledge and visions about the future are enacted in specific contexts. Assemblages are, therefore, socio-technical and comprise people, knowledge, expertise as well as technologies, metrologies and devices. When I talk about *governance assemblages,* I mean the particular attempts to create environments and conditions that render objects or subjects governable. This is most often achieved through the use of epistemic tools, devices, regulations, knowledge creation, etc., but as I have argued here and demonstrate below, these tools do not work alone, but together with the other elements of the assemblage.

The argument about the importance of knowledge creation in governance processes has almost come full circle. I began by arguing how knowledge accounts only highlight particular positions and how difficult it is to create common understandings under scattered agency, only to finish by arguing precisely for the importance of creating knowledge in heat planning processes. I believe this reflection is important. As I have argued here, knowledge is not universally understood all the same and, therefore, planners, researchers and policy makers need to carefully consider which framings, positions and futures they should enact for future heat supply. Simply producing more knowledge will not do as how realities and future visions are made and how they exclude or enable actors to participate must also be considered.

3 METHODOLOGY

The diverse attempts to govern, plan and steer heat supply across countries in the EU are difficult to study. One central aim of this Ph.D. project is to determine to what extend it was possible to describe a European heat sector and the regulation, market-designs, technical infrastructure, user habits and expertise that shape it. In 2, I have already introduced the idea that knowledge creation does not describe an independent reality that exists out there. Instead, theories, methods, tools and experience influence how descriptions of a reality are made. This also applies to the research conducted in this thesis.

However, the fact that reality is not easily accessible by research methods and claims about such realities are the product of the hard work, tools and education of the inquirer does not mean that ‘anything goes’ in terms of making claims about reality. Highlighting how such claims are made and how methods influence the results is an important reflection but it does not mean that any results could have been made:

> “To say something has been ‘constructed’ along the way is not to deny that it is real” (Law 2004, 39)

In the words of Law (2004), methods are “*crafting and enacting necessary boundaries between presence, manifest absence and otherness* (Law 2004, 144). This argument is similar to Latour's (1999) in that it is necessary to reduce the number of inputs describing and object in order to amplify other aspects about that object. Without excluding, black-boxing and reducing the qualities and properties of an object, it is not possible to amplify or highlight other aspects of it. The methodological choices in the thesis help to construct a description of heating infrastructure and planning approaches across the EU-27+UK. I do so with the aim of promoting a new understanding of heat supply as a supply system as well as communicating with other professionals, the research community and decision makers, thereby circulating a new understanding of heating as a potential governance object.

3.1 RESEARCH DESIGN

Therefore, one way of studying heat planning in the EU-27+UK MSs was to deploy different research designs, which all focused on different aspects of the practices, infrastructure, governance and regulation that make up the diverse field of heat planning. Each of the four articles that make up this thesis has deployed a different research design that explores heat planning configurations from different perspectives. Furthermore, they also have different limitations due to their approach and research designs. Broadly speaking, Articles 1 and 4 analyse heating across all EU MSs, while Articles 2 and 3 investigate heat planning approaches through

Table 3.1 Overview of the research designs and focus of the four articles

Article	**Research design**	**Focus**	**Limitations**
Article 1: (Bertelsen and Mathiesen 2020)	Quantitative data analysis Review of available historical data on heating technologies and infrastructure	Analyse current state and historical development of heating equipment and infrastructure in the EU-27+UK.	Only focuses on technical infrastructure. Limited by existing data.
Article 2: (Bertelsen, Paardekooper, et al. 2021)	Literature search Review existing literature.	Analyse how large-scale heating infrastructure has been implemented historically.	Limited to three countries and results are not easily transferred to other countries.
Article 3: (Bertelsen, Caussarieu, et al. 2021)	Interviews and review of plans and reports	Analyse how the practitioners themselves conduct heat planning.	Single case study. Results depend on the specific conditions.
Article 4: (Bertelsen and Mathiesen (Submitted))	Structured data collection with predefined scope and categories.	Analyse how EU-27 MSs plan to transition their energy supply to low-carbon configurations.	Only focuses on the content of the NECPs. Does not consider current legislation or whether measures have been implemented.

specific case studies. Table 3.1 presents an overview of the four articles, their research design, focus and main limitations.

Quantification often allows broader comparisons, but it relies on narrow categories (Bryman 2016) such as energy consumption, capacities, or costs. Article 1 compares 28 countries by using quantitative data, while Article 4 focus on 27 countries by counting the policies, measures and targets deployed in the NECP plans. However, qualitative research also involves reduction. The case study method is an example of how it is necessary to reduce the number of sites to amplify the claims about exactly that case. Article 2 contains three cases, studied by way of a literature review and with an analytical framework with specific categories to structure the empirical material. Article 3 explores how a single case study evolved over a period of 4 years by following the deliberations, negotiations and collaboration between actors. Brighenti (2018) illustrates how specific measurements can black-box the uniqueness of, for example, countries or cities to make them comparable:

> "A city, for instance, can be measured in many ways that make it comparable to other cities through a number of analytic traits, such as population, area, organization, municipal budget, etc. Yet, the uniqueness of the city in which we live, or which we love, possesses a unity and singularity – or a unity-in-singularity – that resists both decomposition into a bunch of traits and aggregation across other comparable urban entities." (Brighenti 2018, 26)

Whereas the messy and uncertain realities are black-boxed in Articles 1 and 4 to enable comparisons between countries, they become more central in the analysis in Articles 2 and 3. Article 2 takes a historical look and investigates the roles of different actors and organisations. In Article 3, technological development and how to navigate such uncertainty is at the centre.

Methodologically, all four articles contribute to answering the research question posed in this thesis. To promote and transition to a new low-carbon heat supply, such diverse contributions are also needed. It is necessary to understand the struggles and uncertainties of actors, the historical role of governments, organisations and utilities in investing and implementing infrastructure, but it is equally important to make new ways of knowing heat supply, not as a fragmented and individual energy demand, but as a connected system. Bringing heating forwards as a new knowledge object will hopefully contribute to the governance tasks of increasing energy efficiency and the amount of renewable energy.

3.2 DESCRIBING THE EU HEAT SUPPLY SECTOR

One of the aims of this Ph.D. thesis is to thoroughly document heat supply in the EU. This was largely achieved by exploring databases, registries as well as information published and curated by organisations, NGOs, research projects and governmental agencies. While initially, this information search also looked for regulations, legislation, and governance models, it became apparent that only quantitative data regarding energy supply, fuels, infrastructure and heating technologies was available across the EU-27+UK. Past research projects, especially the Odyssee-Mure (Odyssee-Mure 2017) and the Hotmaps Project (Pezzutto et al. 2018; Pezzutto et al. 2019), had already collected and published large datasets on heat supply and technologies in the EU-27+UK. Drawing upon the Smart Energy Systems concepts, as present below in 4, the description of heat supply took primary energy supply, distribution infrastructures, final energy consumption and building stock conditions into account. This work is included and published in Article 1.

To examine how European countries are planning to transition their heat supply to decarbonized and efficient supply, another approach was taken. Exploring this vast field of national plans, approaches and legislation was unfeasible. Instead, the National Energy and Climate Plans (NECPs) (European Commission 2021a) were considered suitable for assessing the targets and goals as well as the policies and regulations used by the different countries to decarbonize their energy supply. Still, as the dataset consists of 7408 pages that describe the efforts of 27 MSs[3], an analytical framework for processing the data was required. This study constitutes Article 4. The details of this research are outlined below and in the article in the appendix.

Any approach that claims to consider something in its *whole* will nevertheless exclude other parts, as representations always reduce, frame or highlight specific conditions (Callon 1998; Cilliers 2001). Exclusions occur due to practical reasons or if the inputs are deemed not relevant for the research at hand. In this account of the EU heat supply sector, it was a combination. Article 1 largely relied on the information that was already available. For example, this meant that it was possible to describe the heat supply on an aggregated country level but not in smaller geographical areas. It might have been interesting to see how heat supply differed between urban and rural settings in different countries. As described in the article, significant data about the state of buildings was lacking, which made it difficult to account for the built environment.

This approach is largely descriptive in explaining the development and state-of-the-art of heating, and the targets and policies envisioned to develop it. It becomes more difficult to explain *why* the state of affairs is as it is based on this approach. However, this descriptive approach is beneficial for two reasons. First, it enables a comparison of countries and identification of special cases (Flyvbjerg 2006). Comparing heat supply based on the same quantities highlights which countries differ, which are similar, what types of heat supply are widely used and which types are rarer. As discussed later, this research also informed the case selection in Article 2. Second, it promotes a new understanding of heat supply, which can be used by countries themselves or other research approaches. Analysing heat supply with data on primary energy, conversion, transmission and distribution, building stock and end-use, investigates new perspectives that are currently not addressed together in heat policy and governance, and can potentially advance a new governance approach to heating.

3.3 INVESTIGATING CRITICAL HEAT PLANNING CASES

The case study approach was chosen to explore elements of how heat planning and transitions historically happened and to use a research design with more explanatory

[3] Due to Brexit, the UK did not submit a NECP.

depth to add to the broadly descriptive approaches outlined above. Given the overall interest of this Ph.D. in heat planning and specifically in large-scale infrastructures such as district heating, Article 1 informed the case selection used in Article 2 to decide which cases to explore.

To increase the scope beyond only countries with district heating systems, two cases with high shares of natural gas supplied through transmission and distribution grids were compared to one country with high shares of district heating. The gas countries selected were the UK, the Netherlands and Denmark was chosen as a case with a high share of district heating infrastructure. The initial question that was explored was how and with what purposes these three countries built, planned and maintained these large-scale infrastructures for heating. By investigating similarities and differences between natural gas and district heating grids the hope was that the findings would be applicable and useable in other countries than those already with district heating grids. Additionally, it was explored whether district heating grids had been planned differently than natural gas grids or whether they had relied on similar governance approaches. Analysing the historical development of large-scale heating infrastructures in three countries highlights broadly different periods, the policies used, ownership models, central actors and motivations for building infrastructures.

While Article 2 explore which types of ownership, regulation and drivers were deployed to implement infrastructures, Article 3 explore with a case study how the actors in question themselves navigate these situations. By following the specific development, it was possible to track the uncertainties, how decisions were made and how agreement among actors was achieved. Such uncertainties often disappear in historical accounts (Hanmer and Abram 2017). This approach also allowed us to investigate how actors followed plans and regulation in their daily work, e.g., to investigate specifically how the governance tools worked in an implementation process.

Going in depth with the case studies allow more detailed explanations of how and why certain infrastructures came to be implemented and why certain decisions were taken. Article 2 and 3 adds explanations to the more descriptive accounts of Article 1 and 4. As a trade-off, it is difficult to generalize the finding from Article 2 and 3 to other countries. They present how it was in those specific cases, but these conclusions might not be directly applicable to other cases. I will discuss this further in section 8.5 below.

3.4 RESEARCH METHODS

This section briefly introduces the methods used in the four articles that make up this Ph.D. thesis. The specific details and methodological choices can be found in the method sections of the articles.

Article 1 relied on quantitative data collected from existing databases and research projects. Choosing this source of empirical material made to possible to assess the current extent of existing data about residential heat supply. The most used measure of heat consumption is final energy consumption, and this statistic was central in the analysis. Final energy consumption was found in the Odyssee-Mure database (Odyssee-Mure 2017). By combining this statistic with other data sources, primary energy supply, CO_2 emissions and the share of residential heating technologies could be calculated.

Most of the available data lacked data entries or contained outliers. The specific data handling process is explained in the article. This shows that data from heat supply is difficult to collect as much of it is distributed throughout households across Europe. Without coordinated data collection infrastructure, it is difficult to track the energy consumption, specific technologies used and the state of the building stock.

Article 2 builds upon a theoretical understanding of large-scale infrastructure (Hughes 1987) and its governance to establish an analytical framework for the collection and analysis of data. A central focus was the establishment, role and development of incumbent actors in the development of this infrastructure. While some literature considers incumbents as barriers to new developments (Unruh 2000; Geels 2002), other authors call for analyses of how established actors and organisations can participate in transitions (Berggren et al. 2015; Turnheim and Sovacool 2020). The article thus tracked how actors participated in and changed with technological developments (Jørgensen et al. 2017). Another analytical dimension was the perceived specific qualities of the infrastructure and what societal challenges it would help to solve. By tracking the specific drivers and reasons for investing in the infrastructure, it was possible to record the reasons it had been built and how it changed throughout the periods analysed. The main empirical material was historical accounts in books, academic journals and reports.

Article 3 followed a case of planning and implementing thermal energy storage in Greater Copenhagen for a period of 4 years with 13 interviews and literature reviews as the main methods. Focusing on a single case during a long period gave a deep understanding of the processes, actors and connections that drove the case forward. The research process was, in hindsight, divided into three phases: *exploration*, *continuation* and *follow-up*. The *exploration* phase took place in 2017 with six semi-structured interviews. This first round of interviews explored the challenges related to making the investment in the thermal energy storage and identified the different actor positions and understandings. The *continuation* process gradually began in 2018, when our main focus was to keep track of the development, new changes and proposals from the actors. During this phase, it was possible to follow the negotiations, the plans that were published and investigate how closure formed around the investment. The empirical material collected in the continuation phase mainly took the form of email correspondence, literature and one interview. The third phase, *follow-up,* began in 2019 when the business case and investment model was decided upon. Six interviews were conducted in this phase to investigate how an agreement had been reached, how the actors had shifted their positions and which factors had caused these changes.

While theoretical concepts shaped the interview questions, our approach was not predetermined but followed the empirical material. During the exploration phase, we had not decided that the article would focus on how heat planners use plans, but we were still interested in the role of tools, expertise and models. When the interviews highlighted how the actors navigated uncertain situations using plans, we focused more on the use of plans in the *continuation* and *follow-up* phases. Such an approach that alternates between the empirical material and theoretical concepts and interpretations has been called *abductive* as it "*alternates between (previous) theory and empirical facts (or clues) whereby both are successively reinterpreted in the light of each other"* (Alvesson and Sköldberg 2018).

Article 4 takes a quantitative approach to counting and categorising the content of the NECP plans. The NECP plans are analysed based on the content of two chapters: *National Objectives and Targets* and *Policies and Measures. National Objectives and Targets* mostly contains quantitative goals such as the share of renewables or energy efficiency savings in 2030. The *Policies and Measures* were documented and described according to their attributes, such as targeted energy sector, technology and type of measure. A simple count of measures is used to analyse what policies and measures the MSs use to promote certain technologies. This is a simple approach with certain limitations, but it still represents the overall focus of the NECPs and how the different MSs plan to approach decarbonisation. A major limitation is that the number of measures does not say anything about their effectiveness. One well-made policy can be more effective than 10 poorly designed ones. Still, this approach can describe the focus and content of the NECP plans and, thereby, provide an account of the plans and perspectives of the MSs.

4 TECHNICAL POTENTIALS FOR LOW-CARBON HEAT SUPPLY

This chapter outlines certain concepts and the potential for decarbonising heat supply as a part of a broader energy system. It primarily discusses technical alternatives towards low-carbon energy supply. The chapter present and discuss the current available technologies and their potential for heat supply, which are being promoted in the scientific literature.

Increasing the amount of renewable energy in our energy systems introduces new challenges for the management of energy supply. The fact that energy is a commodity that is available at all times, with the flick of a switch, with the turn of a thermostat or by igniting the gas stove has become a technical norm and widespread expectation. This has traditionally been possible due to the physical properties of stored fuels in the form of coal, gas, oil, biomass or nuclear. When increasing the amounts of wind and solar in the energy supply, the energy must instead be consumed when available. The production logic of the system goes from "production-follows-demand" to "demand-follows-production" (Karnøe 2013).

Smart Energy Systems is an approach for designing and analysing energy systems with the aim of reaching 100% renewable energy supply (H. Lund 2014). The aim of SESs is to combine the electricity, heating, gas and transport sectors to identify least-cost system options (Mathiesen et al. 2015). The Smart Energy Systems methodology includes assessing energy design configurations and scenarios from an energy system perspective, e.g., to analyse how proposed changes impact all the sectors under consideration, and not just a specific energy vector in question (Østergaard 2009; Connolly et al. 2015). With a focus that includes primary energy, energy carriers and end-uses, Smart Energy Systems draws attention to the infrastructures that connects the production and consumption of energy:

> "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 to achieve an optimal solution for each individual sector as well as for the overall energy system." (H. Lund 2014, 11)

Researchers have used the Smart Energy Systems approach to examine topics such as balancing energy savings and supply (Drysdale, Mathiesen, and Paardekooper 2019; Lund, Thellufsen, et al. 2014), to examine where to use a limited biomass supply across different energy sectors (Mathiesen et al. 2012) and electrolyser integration and operation in energy systems (Ridjan et al. 2014; Ridjan et al. 2015). An example of the Smart Energy Systems approach is Hansen et al. (2016), who apply a levelised cost of energy and an Smart Energy Systems approach to the analysis of feasible levels of heat savings in three countries. Their conclusions indicate that the two approaches differ in their analytical approach, and that the Smart Energy Systems approach also identifies supply chain effects from implementing savings, for example, reducing energy consumption also results in a reduced need for energy production capacity. These approaches often calculate what an energy system in a target year, e.g., 2045 or 2050, would need to look like to reach certain objectives, such as low CO_2 emissions, cost-efficiency or energy security in (H. Lund et al. 2021), and from there, deduce the steps that would need to be taken to achieve these futures.

Transmission and distribution infrastructure is central in Smart Energy Systems as it allows the different sectors to interact and utilise energy carriers. Obviously, electricity and gas networks allow the distribution of their energy carriers. Heat can be produced in CHP plants, heat pumps, solar thermal or from geothermal resources among other technologies (R. Lund et al. 2016; H. Lund 2018). Waste heat from energy generation or industrial processes, can be collected and transported through district heating infrastructure, which is especially important from an energy efficiency perspective as it means otherwise lost or unused thermal energy can be exploited, thereby improving the overall energy efficiency of the system. To assess these energy efficiency improvements, it is important to consider the supply chain from production to consumption as losses will be displaced throughout the supply from production to consumption.

4.1 HEATING IN SMART ENERGY SYSTEMS

Heating and its role in energy systems is well developed within the Smart Energy Systems concept. Heat supply can be broadly divided into either collective or individual (Bertelsen and Mathiesen 2020). Individual heat supply is households with their own boilers, stoves or other heat sources, which do not depend on collective infrastructure for the delivery of energy. Biomass, coal and oil heating are in this category. Collective heat supply relies on grid infrastructure to deliver the energy carrier or the fuel for consumption. Gas heating is the most used collective type of heat supply in Europe (Bertelsen and Mathiesen 2020). Electric heating is also a type of collective heating seen from this perspective, although households that use electric heating would often have had a connection to an electricity grid anyway. Electric heating is often treated as individual heating (see, for example Möller et al. 2018).

Several analyses point to the feasibility of DH in future energy systems. Excess or waste heat has high potential with 46% of the excess heat in EU being placed close to centres of high demand (Persson et al. 2014). Exploiting available excess heat can, therefore, significantly reduce primary energy consumption. Connolly, et al. (2015) demonstrate that deploying heat pumps for rural buildings and DH supply for urban areas could result in important synergies between the heating and electricity sectors. DH infrastructure provides access to several renewable and efficient energy sources such as geothermal, large-scale solar thermal, large-scale heat pumps, CHP and excess heat, which could not be exploited without the DH infrastructure (H. Lund, Werner, et al. 2014). Large-scale heat pumps in district heating systems have been shown to integrate fluctuating renewable electricity to produce heat from low-temperature heat sources (Bach et al. 2016; David et al. 2017).

A central aspect determining the feasibility of district heating supply is the distance from heat source and heat consumer as well as the heat consumption density (Frederiksen and Werner 2013). Both these factors influence the grid losses and therefore both the energy efficiency as well as economic feasibility of district heating. From an economic perspective, higher losses will typically mean an increased use of energy and therefore higher costs. Linear heat density, measured in delivered energy per meter of grid network, is often used to measure density of the network. A low linear heat density means low heat consumption per meter of distribution network and vice-versa for a high linear heat density. Denmark has well documented statistics on this topic and serves here as an example. In 2018, the average linear heat density for all district heating systems was 1.9 MWh/m (The Danish District Heating Association 2018). In Greater Copenhagen, where heat consumption is concentrated in urban areas, the linear heat density is higher than average, with Copenhagen Utility reaching 7.8 MWh/m.

Möller et al. (2018) calculated cost-supply curves for district heating supply in 14 EU countries, making up 90% of the heat demand, describing average annualized investment costs for district heating grids as a function of the share of total heat demand. The feasibility of district heating supply differs from country to country, mostly depending upon the heat demand density. For example, while 66% of the Spanish heat demand can be supplied with average annualized investments costs of 2€/GJ, these average investment costs will supply 50% of the heat demand in Germany and the Netherlands and below 20% in Hungary and Romania. (Möller et al. 2019) show that up to 71% of residential heat demand in urban could be connected to district heating systems, and 78% of this could be supplied with excess heat.

Lund et al. (2014) present how DH can be part of future decarbonised energy systems within the Smart Energy Systems approach with the concept of 4th Generation DH (4GDH). 4GDH is an attempt to identify the role DH could play in future decarbonised energy systems, including how to integrate renewable energy and establish a balance with energy efficient buildings (H. Lund, Østergaard, et al. 2018). Central to the 4GDH concept is a reduction in the supply and return temperatures, which decrease energy losses and increase the number and efficiency of potential supply sources (H. Lund, Østergaard, et al. 2018), as well as significant cost reductions (R. Lund et al. 2017).

In order to realise a transition to 4GDH systems, Lund et al. (2018) list a number of technical changes that must be made. First, the lowering of return and supply temperatures entails significant changes to building systems, space heating and domestic hot water supply, substations and potentially booster heat pumps, DH networks as well as the production units. Changes to radiator systems or increasing radiator sizes can accommodate low-temperature supply. Domestic hot water should be able to function without legionella issues and with short waiting times for hot water (H. Lund, Østergaard, et al. 2018).

While existing district heating grids can be utilised in 4GDH systems, moving towards new supply units may entail new grids if the supply is placed at new locations. Therefore, both existing and new district heating systems will require investment in district heating transmission and distribution infrastructure (H. Lund, Østergaard, et al. 2018). If pipes are replaced, it is usually feasible to invest in increased insulation to limit losses (Frederiksen and Werner 2013; H. Lund, Werner, et al. 2014).

4.2 FROM POTENTIALS TO IMPLEMENTATION OF DISTRICT HEATING

District heating systems have technical potential but they also face a number of barriers. Significant work, coordination and building time is required for such large-scale infrastructure (Hughes 1987). They have long lifetimes and investors will, therefore, need to be sure that such infrastructure remains relevant in future energy systems. The infrastructure must often be implemented in urban areas such as transmission and distribution pipelines or heating equipment within buildings. District heating systems also constitute monopoly situations in terms of transmission and distribution infrastructure. Building competing supply systems is usually too expensive (and unfeasible due to the aforementioned factors) and it is also expensive for users to disconnect if they already use district heating. Therefore, the ownership, regulation and access to the grid infrastructure is important to take into account. All these challenges are not impossible to solve and have been overcome in many places. However, they are factors that actors, investors and decision-makers will probably have to deal with.

The fact that district heating grids represent collective infrastructure that connects producers and consumers together through supply networks means that a number of actors have to cooperate to enable the system to function. Often a Transmission System Operator (TSO) or Distribution System Operator (DSO) is responsible for grid operation and maintenance, setting temperature and pressure levels. However, just on the production side, several actors need to coordinate their actions. CHP plants that produce electricity according to the electricity price, waste incineration that deals with municipal waste, other excess heat sources that depend upon the availability of heat, all plan their production according to a number of different elements. A number of producers are set to participate in district heating systems with their diverse personal understandings of the system. With heat pumps, thermal storages and unconventional heat sources, the number of producers is bound to increase. Governance and regulation that enable the participation of these diverse actors is one challenge facing future district heating systems.

This chapter has highlighted some of the main arguments for using district heating in future low-carbon energy systems. District heating is often framed as a cost-efficient supply system that enables the integration of renewable energy, increases energy efficiency and overall energy system flexibility. It represents a way of increasing choice awareness of the potential of different technological solutions, but it does not mean that these solutions will necessarily be chosen and implemented. Other energy imaginaries advocate electricity-hydrogen energy systems (van Wijk and Wouters 2020), which would potentially fit well with existing natural gas infrastructure. Such discourses are, for example, promoted by UK gas actors in their attempts to maintain their market positions (Lowes et al. 2020). Other academic approaches rely entirely on the electrification of end-use demands by expanding wind, hydro and solar power (Jacobson and Delucchi 2011).

All of these socio-technical imaginaries deploy epistemic devices to qualify their technical alternatives. Rather than asking which plan and strategy is most correct, the outcome and choice of strategy depends on how successful they are at mobilising actors and stakeholders, how new technologies fit with existing infrastructure and systems, as well as the current regulatory and institutional settings. These issues are addressed in the next chapter, which discusses the literature on energy planning.

5 CRITICAL REFLECTIONS ON THE ENERGY PLANNING LITERATURE

This section discusses different approaches and understandings of energy planning and the implementation of new technologies from the energy planning literature. In a review of the literature concerning municipal energy system planning, Weinand (2020) shows that the most frequent topics covered are *fuels*, *thermodynamics* and *environmental science*. The most frequent social science topic is *economics,* which is covered by 7% of the 1,235 publications (Weinand 2020). In the literature on 4th generation district heating, Lund et al. (2018) argue that planning and implementation is one of the greatest challenges facing the transition to a low-carbon energy supply:

> "The status of the scientific contributions demonstrates a high level of understanding of how to deal with the technical aspects. The primary current challenge seems to be the understanding of the implementation, in which a local understanding of the concrete conditions as well as the legal framework is needed" (Lund, Duic, et al. 2018, 617).

Although the literature is still primarily focused on technical matters, progress is being made towards integrating questions of implementation, transitions, adaptation of new energy supply as well as habits and practices of energy use into energy research (Sovacool et al. 2015). In another literature review, Krog and Sperling (2019) found that there are diverse interpretations of what *Strategic Energy Planning* entails. They argue that a wide range of different sectors is covered by the literature. Some journal papers only focus on the electricity sector, some focus on electricity and heating, while only a few focus on what they term *the entire energy system*. Over half of the reviewed articles did not specify which sectors or technological parts of the energy system were being addressed (Krog and Sperling 2019). Building on the theoretical discussions in 2, in the following, I analyse how certain authors understand the energy system and the activities that must be completed in order to move towards a low-carbon energy supply.

5.1 TOWARDS AN UNDERSTANDING OF LOCAL AND DECENTRALISED ENERGY SYSTEMS

Central to the literature on energy planning is the notion of increasing technological *decentralisation* and *local* energy supply (Bush et al. 2017; Krog and Sperling 2019; Weinand 2020). It is argued that renewable energy (Weinand 2020) or district heating (Bush et al. 2017) is inherently *decentralised* compared to other types of energy supply.

> "As a decentralized infrastructure, the facilitation and coordination of new district heating development necessarily takes place at the local level" (Bush et al. 2017, 140).

Bush et al. (2017) equate the changing technological configuration of energy supply with a need for local planning: "local energy systems need local governance" is the argument. Krog and Sperling (2019), likewise, argue as follows:

> "Some new parts of the energy supply, conversion and integration infrastructure are constructed closer to the consumers, in the form of e.g. wind turbines, combined heat and power plants (CHP), district heating, electric vehicle charging stations, biofuel plants, electrolysers" (Krog and Sperling 2019, 83).

New low-carbon energy supply is often considered to be more *local* or *decentralised,* as highlighted by the two quotes above. But what does it mean if a technology is *decentralised* and how can one type of technology be *more local* than another?

In spatial terms, local often refers to a specific area and local planners are often equated with the local government or authority of this specific location. Considering the term *local* in spatial or geographic terms, governmental levels and their respective areas of responsibility are strictly defined in public registries. Boundaries in the form of NUTS and LAU standards can be downloaded from Eurostat for all of the EU Member States (Eurostat 2021). However, it is often not easy to contain local planning, action and governance within specific geographical areas, as we will see in the following.

Cities as the main sites of action

Urban authorities are already involved in much infrastructural development within their respective boundaries (Kern and Bulkeley 2009). Cajot et al. (2017) argue for a new role for urban governments facing energy transitions. They equate local governments' increasing energy responsibility with the need to make changes within their own geographical administrative boundary:

> "Cities formerly might have been considered only as "centers of passive demand which must be supplied from an ex-urban source" (Keirstead et al., 2012), but today must play a more active role in organizing their energy systems from within their geographical boundaries" (Cajot et al. 2017, 226).

Here, there is a direct connection between the decentralisation of energy technologies and their governance and planning. The argument is that as technology becomes more decentralised, local and closer to citizens, so must the governance, planning and administration (Cajot et al. 2017; Krog and Sperling 2019). However, cities are not alone in planning and managing their energy supply. Cables connect the electricity supply to national transmission systems, fuel is imported and not all energy is produced within urban boundaries. Urban energy systems remain technically connected to other parts of the energy system: it is even difficult to make a sharp delimitation of what constitutes an urban energy system (Maya-Drysdale et al. 2020; Johannsen et al. 2021). Even DH systems, which could be argued to be confined to the specific areas where their distribution grids reach, still engage with international electricity systems through CHP production. Cities inherently depend on vast hinterlands for their energy and resource supply (Monstadt 2009). In the case of district heating, changing from individual boilers to district heating supply entails the centralisation of supply for the heat consumer. Instead of heat consumers having control of their own individual heat supply unit, district heating systems supply the heat through transmission and distribution infrastructure.

The emphasis on the local highlights the importance of the actors who implement technologies as they make investments, prepare the development plans for particular systems and manage the day-to-day operations (Walker and Devine-Wright 2008; Damsø et al. 2016). However, such a delimitation of the local tends to ignore the assemblage that enables them to act, i.e., their tools, the regulations, and the financial conditions. Building on 2 and the presentation of socio-technical assemblages (Çalişkan and Callon 2010), such planning activities do not occur in a vacuum as they depend on a diverse set of heterogeneous elements such as regulations, legislation, expertise, planning tools, etc. In their study of Danish heat planning, Chittum and Østergaard (2014) argue that there is a similar lack of focus on the socio-technical assemblages that enable cities, municipalities, utilities and other stakeholders to invest in energy infrastructure':

> "Little academic attention has been paid to two significant aspects of Danish energy policy: the specific tools and powers granted by the national government to Danish municipalities that have resulted in the expansion and continued investment in cost-effective DH systems, and the unique autonomy of cities to make their own long-term decisions about their energy future as it relates to heat." (Chittum and Østergaard 2014, 466)

Several of these energy planning approaches and accounts that prioritise the *local* do not consider the diverse assemblages that enable planning and investments in energy systems. Renewable energy in particular seems to be understood as more *local* than for example large fossil fuel power plants, but another interpretation of this is that these two different technologies simply engage in socio-technical assemblages in different ways.

Coordination among local and non-local actors

Although the local level is often prioritised as the main site of action, many authors acknowledge a necessary connection between local/urban actors and actors in national governments, agencies, regulators and others. Bush et al. (2017) argue that "*the local nature of district heating means that a systemic intermediary response is needed across the geographical scales to support empowerment*", while Krog and Sperling (2019) argue that communication between levels is necessary to ensure that system development moves in the same direction. The multi-level governance approach is one strand of literature in which authors advocate connecting different levels of government together. They highlight the need for *local* action but within a governance system that connects the local with regional, national and supranational authorities (Jänicke 2015; Dobravec et al. 2021). These interactions are not always free of conflict as "*multi-level issues tend to reflect complex and unstable patterns of power and resistance rather than stable co-operation processes*" (Jaglin 2014, 1395). While such governance processes may be the subject of power struggles and resistance to change, they are also scattered across multiple agents who all try to navigate uncertain situations, as already argued in 2. Coordination between actors does not just entail power struggles but also the creation of common understandings and realities (Farías and Blok 2016; Iuel-Stissing et al. 2020).

Heaphy (2018) shows how such communication occurs in a study of London and Manchester: It involves a complex assemblage of empirical analyses, modelling, technical standards and metrologies to produce knowledge claims about the specific situations in which stakeholders exist. To engage in governance and policy processes across multiple stakeholders, cities need to produce statements and facts about their situations.

Sperling (2017) provides another example of the difficulty in keeping such transitions local. In his case study of the Danish island, Samsø, and how it became internationally recognised for the deployment of renewable energy, Sperling (2017) highlights the importance of several elements in realising this transition. Entrepreneurial individuals on the island and a tradition for community ownership combined with expert consultants, national regulation and financial support, guiding visions and strategies both for Denmark as a whole as well as for Samsø, market regulation and conditions, wind turbines specifically developed to be available for community ownership in addition to an electricity transmission cable that allowed to import and export electricity all formed part of the transition to what is termed *"The Renewable Energy Island Samsø"* (Sperling 2017). The transition was local in the sense that it happened in at a specific geographical location, Samsø. However, at the same time, the transition, planning, actors and drivers could not be contained within that geographical area alone. Instead, a socio-technical assemblage of actors, technologies and regulation facilitated the deployment of wind turbines on Samsø; a network which is both local and global at the same time. What was important was that several actors were able to combine their efforts. Avoiding focusing on which elements are *local* or *global* and instead looking at the socio-technical assemblages highlights how agency is facilitated and emerges in the particular situation (Latour 2005). Instead of a priori assuming that local factors are of the highest importance, this should instead be treated as an analytical result.

Energy planning as assemblages instead of discrete local sites

To summarise, some energy planning approaches prioritise *the local* as the primary site of action as well as local actors as the main protagonists of energy planning processes. This understanding seems to prioritise geographically *local* factors, but black-boxes other factors such as national regulation and large-scale infrastructural systems, which interact and influence *locally* just like other actors and objects in the socio-technical assemblages. While being sensitive to local conditions is no doubt of paramount importance when implementing technologies, such approaches sometimes lack attention to the enabling socio-technical assemblages due to the framing of the local being disconnected from “non-local” sites. First, technology is obviously local in the sense that it is placed in a specific environment. This is the case for all technologies, individual boilers, wind turbines, nuclear power plants, etc. Some technologies are not more local than others. It is not the fact that a technology is local that produces emergent effects, but rather the situation into which it is placed (Walker and Devine-Wright 2008). Therefore, the fact that a technology is local is not of analytical importance. However, what is important is *how* the technology is local and into which socio-technical assemblages it is placed. This applies to all technologies. Second, as outlined in section 5.1, energy systems are difficult to keep local. They are increasingly being interconnected across sectors and scales. In contrast to individual heating, district heating systems represent collective infrastructures that distributes heat from production sites to consumers. District heating is often connected to other sectors such as electricity through CHP plants or heat pumps. Wind turbines that are owned by citizen collectives still sell their electricity on the electricity market or for Feed-in-Tariffs determined by a national government. These systems might have decentralised parts, but they still depend on interconnecting grids and transmission systems. Third, just as technology is difficult to keep local, so are the governance arrangements that enable and equip actors to interact with their objects of governance. The Samsø case shows that the tools, devices, expertise and regulation that enabled the actors to engage with the transition were produced on the island and in other places (Sperling 2017). The assemblage that enabled and produced action on Samsø was the emergent effect of national regulation, engaged citizens, expert consultants, wind turbine manufactures, market conditions and so on.

This discussion of how authors in the energy planning literature understand technologies has underlined two perspectives. First, the distinction between local and global is problematic as it omits certain central aspects and prioritises certain sites of action. Second, the governance of energy systems and low-carbon energy supply should be understood as an assemblage of both local and global elements that are always applied and used in specific local situations. Building on these two points, the following section discusses how energy planning, governance and the steering of transitions should be conducted according to various authors in the literature.

5.2 HOLISTIC, STRATEGIC AND INTEGRATED ENERGY PLANNING

While the section above discussed the delimitation and framing of energy transition accounts in the academic literature, this section focuses on how energy planning processes should be carried out according to authors in the literature. How should change be governed, new innovations implemented and transitions facilitated when they are all inherently uncertain, difficult to define and subject to the multiple understandings of the stakeholders involved? A common methodology for planning and acting in these highly complex systems is to commence with knowledge production:

> "While subscribing to the idea that a complex system description is dependent on the point of view of the researcher (Cilliers, 1998; Kljajiae, Škraba, & Bernik, 1999), our approach towards building this framework is to map the UES [Urban Energy System] in its entirety, complete with its structure, layers and elements, along with their networks, interactions and interlinkages with other elements of a city" (Basu et al. 2019, 3).

Basu et al. (2019) assert that although complex systems are difficult to know and describe, and any description will be influenced by the position of the observer, researchers should still attempt to map them "*in their entirety*". By integrating more perspectives into analytical approaches to energy planning, the argument is that these uncertainties can be made known and thereby solved. Certain authors on energy planning approaches for cities advocate for the integration of energy planning into other municipal areas of responsibility, developing energy planning practices and expertise as well as creating visions and pathways for future low-carbon supply (Maya-Drysdale et al. 2020). Moving the energy planning focus to urban actors has resulted in the reframing of the content of analysis and an argument for broadening the scope of analysis:

> "In order to incorporate and address energy and sustainability issues, urban planning processes must transcend former spatial, temporal or sectoral boundaries" (Cajot et al. 2017, 227).

It is often argued that when approaching energy sustainability with an urban focus, energy challenges should be seen together with other urban or geographical agendas, involve the stakeholders that form part of the processes, and analysis of the potential barriers to implementation of the plans should be conducted. Broadly speaking, the argument is to expand knowledge generation to encompass all aspects to produce a holistic representation of reality.

Thery and Zarate (2009) assert that energy planning as a multi-stakeholder process across the energy supply chain to achieve optimal configurations of different energy sources. From their point of view, it is a complex issue which should involve a combination of environmental, safety, social and geopolitical criteria across multiple temporal and actor scales. They suggest that multi-criteria decision-making and mathematical, stochastic or hybrid optimization strategies can deliver optimal configurations given these multi-stakeholder environments and complex issues. They do not discuss how actors agree on optimisation criteria, what optimal energy futures should look like or identify common issues among complex interactions.

Mirakyan and De Guio (2013) present a four-step model for *integrated energy planning*, which consists of: 1) preparation & orientation, 2) detailed analysis, 3) prioritisation & decision-making and 4) implementation & monitoring. They argue that the four steps do not represent a linear process as several iterations through the steps are often necessary. Starting out in phase one, *"the initial situation is roughly analyzed, the problems are formulated, the potential solutions are listed and the objectives and the targets are set"* (Mirakyan and De Guio 2013, 292). For example, actors are supposed to align visions and gain a common understanding of the situation. While Mirakyan and De Guio (2013) include multiple stakeholder perceptions in their model, it is still presented as a process leading to optimal outcomes through informed deliberation and analysis. Uncertainty is information waiting to be discovered in order to facilitate implementation, and when the master plan has been defined, this is sufficient to aid the implementation of novel technologies.

Geels et al. (2020) propose combining energy system models with the Multi-Level Perspective to integrate long-term visions of desired futures with tensions in current systems, path-dependencies and lock-in into what they term Socio-Technical Scenarios (STSc). The aim of the approach is to combine expert knowledge from energy modelers and transition researchers to identify the direction in which energy systems should ideally develop and any challenges that may be encountered on the way. While advocates of the approach argue that, *"model-based scenarios pay limited attention to the actors, organizations and activities that ultimately bring about transitions"*(Geels et al. 2020, 1), the STSc approach itself remains expert-based and detached from scattered actor involvement, uncertainty, and the many different emergent situations and understandings that may be present in energy planning situations.

Authors behind a strand of research in the urban energy planning literature take a complexity approach (Bale et al. 2015; Basu et al. 2019) and argue that cities are made up of complex systems, one of which is the energy system. These systems interact, feedback and influence each other in complex and emergent ways (Bale et al. 2015). It is argued that these intertwined urban systems produce *wicked problems* (Cajot et al. 2015; Maya-Drysdale 2020), which are inherently difficult to define, understand, and make tangible. These problems are generated by the multiple stakeholders, their interests, opinions and understandings of uncertain situations (Cajot et al. 2015).

Such arguments for holistic approaches to navigate wicked problems of uncertainty assume that there is a single knowable discrete socio-technical object or system *out there*. By increasing the complexity or inputs into the epistemic tools used to bring the object into being, its properties, qualities and merits become visible, and perhaps most importantly, they become visible to actors in the same way. Thus, agreement and closure are reached through knowledge creation. Such approaches take a *governance on the outside* perspective (Smith and Stirling 2007) by assuming that there is a discrete and ultimately knowable object that can be discovered.

In line with the theoretical discussion in 2, such approaches fail to take several aspects into account. First, approaches that define socio-technical systems *in their entirety* are ineffective as these systems will always be known through particular framings and with the epistemic devices of actors. An object or system cannot be known independently of the tools, expertise or methods it is connected with or without the data, qualities or measures by which it is evaluated and measured. Second, assuming that more complex understandings of socio-technical systems leads to closure and agreement also assumes that such knowledge will be automatically accepted and adopted by the actors which it seeks to convince. However, this is not necessarily the case, as actors operate with their own epistemic networks, expertise and tools (Çalişkan and Callon 2010). Third, arguing for more complex epistemic devices assumes that the actors have the capacity, knowledge and resources to operate such epistemic infrastructure, but this requires significant investment in building expertise. Next, I briefly address the problem of a lack of resources among energy planners, as it is they who predominantly use, apply and conduct energy planning analyses according to much of the planning literature.

5.3 LOCAL PLANNING CONDITIONS: EXPERTISE, RESOURCES AND PURPOSE

The academic literature has produced several accounts of the conditions that municipalities, energy planners and utilities act under, the expertise and resources they have at their disposal and how they seek to integrate decarbonisation goals into their strategies, visions and everyday work.

Krog (2019) identifies several challenges for Danish municipalities when conducting energy planning including a lack of communication with other governmental levels, changing rates of subsidies and taxation, the fact that energy planning is a voluntary task in Denmark, a lack of clearly defined long-term goals and a change of political focus resulting from elections. In their analysis of three ambitious cities in the UK and their energy plans, Webb et al. (2016) show that although the cities attempt to implement renewable energy solutions, there is a gap between ambition and capacity to act. Austerity in public financing, a reliance on market instruments and the limited technical ability of municipalities result in small-scale scattered initiatives instead of strategies supporting systemic shifts (Webb et al. 2016). In the Netherlands, municipalities were found to lack resources and motivation among administrative staff (Vringer et al. 2020), while Ben Amer et al. (2020) argue that expertise and knowledge is insufficient to apply energy system analytical tools in Danish municipalities. Local governments in the UK and Germany are increasingly working to enable forms of governance under financial pressure and increased privatisation and liberalisation, which are often driven by the EU (Bulkeley and Kern 2006). In their review of energy visions in eight European cities, Maya-Drysdale et al. (2020) argue that while the cities have ambitious visions, they are often not related to overall energy system developments, large-scale decarbonisation or transitions to 100% renewable energy systems. Instead, the cities' energy visions are mostly concerned with urban development and there is a lack of integration between energy sectors and short term perspectives are applied. Municipalities struggle to implement abstract plans formulated by national actors as they do fit the urban-local realities: something is lost in translation between national and local policy making (Petersen 2018). This highlight a central aspect of understanding *Governing at a Distance*, specifically that regulation, policy and steering does not work in a linear and predictable fashion, but will be interpreted in the specific situation. This highlights the situatedness of energy actors and their particular views of energy systems based on their own perceptions (Iuel-Stissing et al. 2020). If plans and strategies do not interest and do not include particular roles for the actors in question, they may lose relevance. Several authors point to the fact that while several success stories have been documented in the energy planning literature, this still leaves many average-performing cities without a clear pathway to decarbonizing their energy supply (Petersen 2018; Krog 2019).

Allman et al. (2011) surveyed progress made by Welsh and English municipalities in terms of climate change mitigation and found three common factors among the municipalities that had developed and implemented local plans, goals and measures. First, the municipalities had identified potential benefits of their strategies in terms of employment, quality of life or reductions in fuel poverty. Second, they had strong political, professional and technical support. Third, they developed successful partnerships with utilities, private, public and voluntary groups. Again, this demonstrates that energy transitions must be made relevant to the particular situation (employment, quality of life, etc.) with the right knowledge and expertise (support) and should build upon assemblages of actors, knowledge, regulation, etc.

To summarise, several factors inhibit the agency of municipalities to act towards decarbonising energy supply in a coordinated way. First, researchers point to a lack of communication between municipal, regional and national actors (Petersen 2018; Krog 2019). Second, there are challenges regarding connecting long-term visions with short-term action (Webb et al. 2016; Maya-Drysdale et al. 2020). Third, there is a lack of knowledge, resources and motivation to carry out energy planning processes (Webb et al. 2016; Ben Amer et al. 2020; Vringer et al. 2020). Proposing new energy planning approaches should take these limitations into account. New governance regimes for energy planning should help energy planning actors render uncertain situation actionable, not impose complicated and abstract knowledge production devices upon them.

5.4 ENERGY PLANNING UNDER PARTIAL FRAMINGS AND UNCERTAINTY

This chapter has discussed the following three central issues with regard to energy and heat planning: many authors in the literature treat the *local* as the primary site of action; planning approaches require *holistic* understandings; the resource capacities of municipal and local planners, experts, utility workers and decision makers.

To summarise, this discussion of strands in the energy planning literature has identified controversies that limit the effectiveness of contemporary governance approaches. First, the term *local* is often used without a strict definition. Describing objects or subjects within the term local often imposes certain limitations on the analysis: a local scale does not mean that there is no connection to the outside world. Following Latour (2005), renewable technologies and the actors managing and investing in them act through particular connections and intermediaries. Being local does not inherently contain specific properties; these are rather produced through the particular assemblages the socio-technical object is placed within.

Second, it is often argued in energy planning approaches that holistic methods can make their objects known in their entirety. This assumes that discovering the inherent qualities of a socio-technical object will produce collective agreements among actors. This lacks sensitivity to reflexively considering the influence epistemic devices, knowledge and expertise have on how these objects are brought into being in particular ways. Accounts of socio-technical objects will always be particular framings that highlight certain aspects while rendering others opaque (Callon 1998; Latour 1999).

Third, the municipal actors who often conduct energy planning frequently lack resources, knowledge and expertise as well as communication and coordination with other organizations. More complex, holistic and integrative tools may be too complex and abstract to tackle the daily tasks of a municipality. Instead, epistemic tools for municipal energy planning should be able to highlight specific benefits of interest and bring into being the district heating solutions in ways that are relevant to the municipality.

As with any trade or business, central to energy planning are the tools, methods and expertise that produce the goods that circulate among the users. This review has shown that authors often argue for expanding their model tools to include more aspects and factors in the search for more accurate representations of reality. This reflects an ontology that assumes the world can be known objectively and singularly. Instead, the models, tools, scenarios and strategies so often produced and used in energy planning practice do not simply describe reality: instead they form part of making reality, and in making reality tangible they make it governable, and make action possible. Researchers of energy planning need to start considering how realities can be built and mobilised to support new low-carbon futures. New knowledge is central to such an approach, but it is important to recognise that simply advocating more complex and holistic accounts will not be sufficient.

6 EUROPEAN HEAT SUPPLY AND FUTURE TARGETS

This section provides an account of the historical development and current state of residential heat supply (based on Article 1) combined with a description of the goals and measures the countries in the EU are planning to implement to transition their heat and energy supply towards 2030 (based on Article 4). Together, these two articles provide an account of the current state of affairs and how the countries in the EU plan to move forward with their heat supply.

6.1 HISTORICAL AND CURRENT HEAT SUPPLY

This section primarily builds on the results of Article 1 and serves two main purposes. First, to provide an overview of the historical development and current status of the EU-27+UK heat sectors. Second, it serves as an attempt to bring heat supply forward as a governance object, to enact a description of the historical and current conditions. The section presents a summary of the findings outlined in the article and moves on to discuss their implications for the EU-27+UK heat sectors.

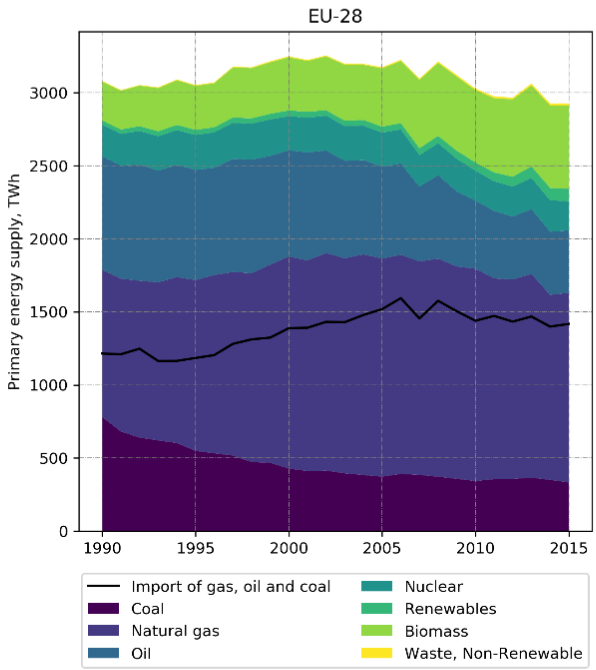


Figure 6.1 Historical primary energy consumption for residential heating in the EU-27+UK from 1990-2015 (Bertelsen and Mathiesen 2020).

6.1.1 PRIMARY ENERGY CONSUMPTION FOR RESIDENTIAL HEAT SUPPLY

70% of the residential heat supply in the EU-27+UK is based on fossil fuels, with the majority coming from natural gas. Figure 6.1 presents the development of the primary energy supply for residential heating from 1990 to 2015. Total primary energy supply has been decreasing since 2000 with 2015 being the lowest year in the period. Throughout the period, the amount of imported fuels in terms of gas, oil and coal increased and in 2015, 69% of the fossil fuels used in EU-27+UK residential heating were imported.

Figure 6.2 shows the related CO_2 emissions from the EU-27+UK residential heat consumption. While CO_2 emissions from oil and coal consumption decreased from 1990 to 2015, emissions from natural gas increased to 53% of the total CO_2 emissions from residential heating in 2015. CO_2 emissions from biomass consumption for residential heating are currently not accounted for in the EU's CO_2 accounting schemes, as biomass is considered climate neutral and CO_2 emissions are counted in the forestry sector (European Commission 2021b). The feasibility of high biomass consumption, especially as a fuel for heat supply (Mathiesen et al. 2012), as well as the current CO_2 emissions accounting methods (Birch Sørensen et al. 2018) have also been questioned. If CO_2 emissions from biomass are to be accounted for in the energy

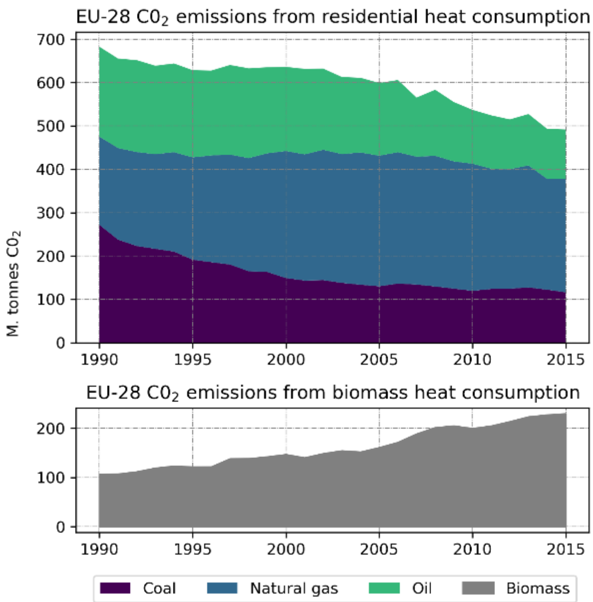


Figure 6.2 Estimated EU-27+UK CO2 emissions from residential heat supply (Bertelsen and Mathiesen 2020).

sector, the direct CO_2 emissions from biomass would almost reach the level of emissions from natural gas, which would negate the overall trend of CO_2 emission reductions since 1990.

6.1.2 LARGE-SCALE INFRASTRUCTURE FOR RESIDENTIAL HEAT SUPPLY

Figure 6.3 shows the single most used type of heating in each country of the EU-27+UK based on the distribution infrastructure used, which is district heating grids, gas grids, electricity grids or no central distribution infrastructure such as biomass, coal and oil heating. Only in three countries, Denmark, Sweden and Finland, is district heating the single most used type of residential heating. In Belgium, Germany, Hungary, Italy, Luxembourg, the Netherlands, Slovakia and the United Kingdom, gas heating is the most used type of residential heating. This shows that 11 countries out of the EU-27+UK have deployed large-scale heating infrastructure for heat supply to such an extent that it is the most used type of heating.

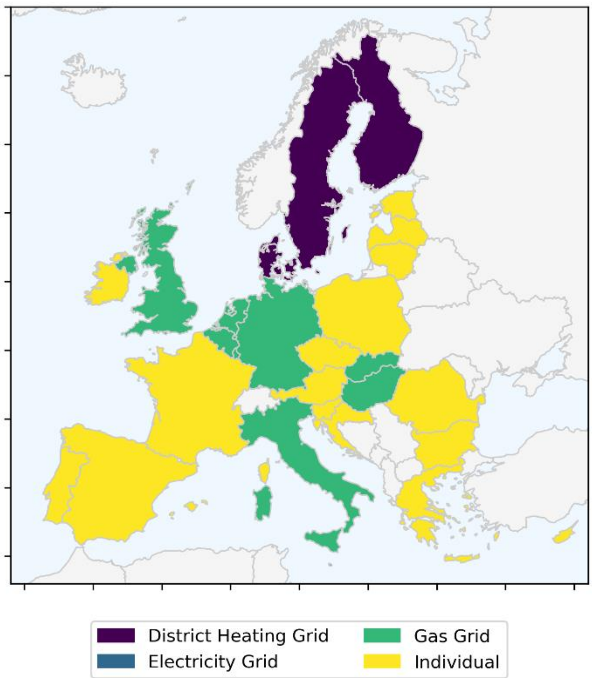


Figure 6.3 Geographical representation of the single most used type of residential heating infrastructure or individual heating (oil, coal, biomass) per country in the EU-27+UK (Bertelsen and Mathiesen 2020).

While the implementation of such large-scale infrastructure is explored in depth with three cases studies below in 7, the widespread use of gas networks shows that most countries in the EU have managed to deploy large-scale infrastructure for heat supply. Potentially, these experiences can be used for investing in district heating networks.

6.1.3 FINAL ENERGY CONSUMPTION FOR RESIDENTIAL HEATING

Figure 6.4 shows the residential heating consumption per country in the EU27+UK in 2015. Germany, France, the UK and Italy together constitute 60% of the residential heat consumption for the EU27+UK. Figure 6.4 also shows the diversity of supply systems in the different countries, with most countries having several different supply technologies and many different configurations between the individual countries. Even with an aggregated national perspective, the different heat supply systems are diverse across the EU, without taking into consideration the different configurations at the urban or regional scales.

Figure 6.5 shows that although the amount of occupied living area increased from 2000 to 2015, the space heat consumption decreased while domestic hot water consumption remained stable. The colored bars also show the change in the intensity

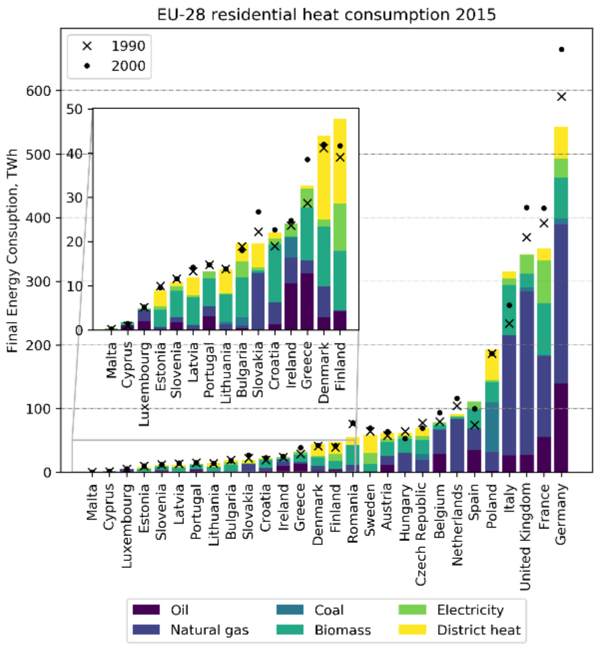


Figure 6.4 Final energy consumption for residential heat in the EU-27+UK countries in 2015 (Bertelsen and Mathiesen 2020).

of residential space heat consumption, measured by kWh space heat consumption per m^2 occupied living area. This shows the shares of the total residential heat consumption, that are taken up by different space heat consumption intensities. The graph shows that the high intensity (~250kWh/m^2) space heat consumption living areas reduced their share and had disappeared by 2010. Overall, the share of buildings with an average consumption below 150 kWh/m^2 increased to make up most of the EU-27+UK building stock in 2015.

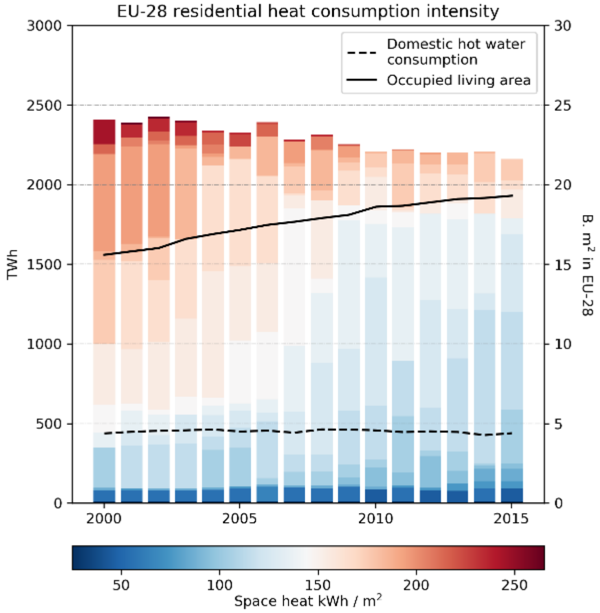


Figure 6.5 Space heat and domestic hot water consumption. Total consumption shown on left y-axis and colored bars show the space heat intensity measured in kWh/m^2 (Bertelsen and Mathiesen 2020).

6.1.4 TECHNICAL HEAT SUPPLY CONDITIONS IN THE EU-27+UK

The section above has presented an account of heat supply by taking into account primary energy supply, CO_2 emissions, infrastructure, final energy consumption and residential heat consumption intensity. However, this should not be seen as a full description of EU-27+UK heat consumption but as an attempt to connect these aspects of heating that were previously considered as separate elements. The account of residential heat supply is also limited to the currently available empirical data.

The section illustrates that on an aggregated European scale, fossil fuels dominate residential heat supply accounting for 70% of the fuel consumption with much of it being imported. Due to a shift in fossil fuels from coal and oil to gas, CO_2 emissions decreased from 1990 to 2015, although they might be considered stable if accounting for all emissions from biomass. While district heating systems represent the single most used type of heating in only three countries, natural gas grids are the most used type of heating in 8 countries. Therefore, several countries do use large-scale infrastructure in their heat supply. Final energy consumption for residential heating has been decreasing since 2000, although the number of occupied square meters has increased, signaling an increasingly efficient building stock.

6.2 ENERGY SYSTEM TARGETS AND MEASURES

This section presents the main results from Article 4. This section focuses on the results in the light of heat supply and how this is treated compared to other energy sectors and supply.

6.2.1 TARGETS AND GOALS

Figure 6.6 below shows the targets for renewable energy in 2030 for the overall energy supply (A), electricity (B) and heat supply (C). The weighted average target for 2030 for the share of overall energy supply that is renewable energy is 33%. This was calculated by weighting the targets with final energy consumption. The average target for renewable energy as a proportion of total heat supply is also 33%, while for the four countries with renewable energy targets for district heating, the average target is 69%. The average target for renewable energy in electricity supply is 52% across the EU27.

This shows that the EU27 member states are on average more ambitious with regard to renewable energy in their electricity supply than in heat supply. The member states are in fact just as ambitious for their heat supply as with the overall decarbonisation of energy, as both average targets are 33%. The most ambitious countries regarding renewables in their heat supply seem to be those with district heating as Denmark, Estonia, Finland and Lithuania all report high renewable energy targets both for district heating and heating in general. District heating also accounts for a high share of heat supply in Sweden and Latvia and they have high targets for renewable energy for heat supply, in general, but no separate targets for renewable energy for district heating.

As presented in 4 on technological potentials, there are several technical solutions for a decarbonised and efficient heat supply. It seems that these have been adopted by some, but not all countries, as countries with specific targets for district heating are ambitious, while those without specific district heating targets also lack high overall heating targets.

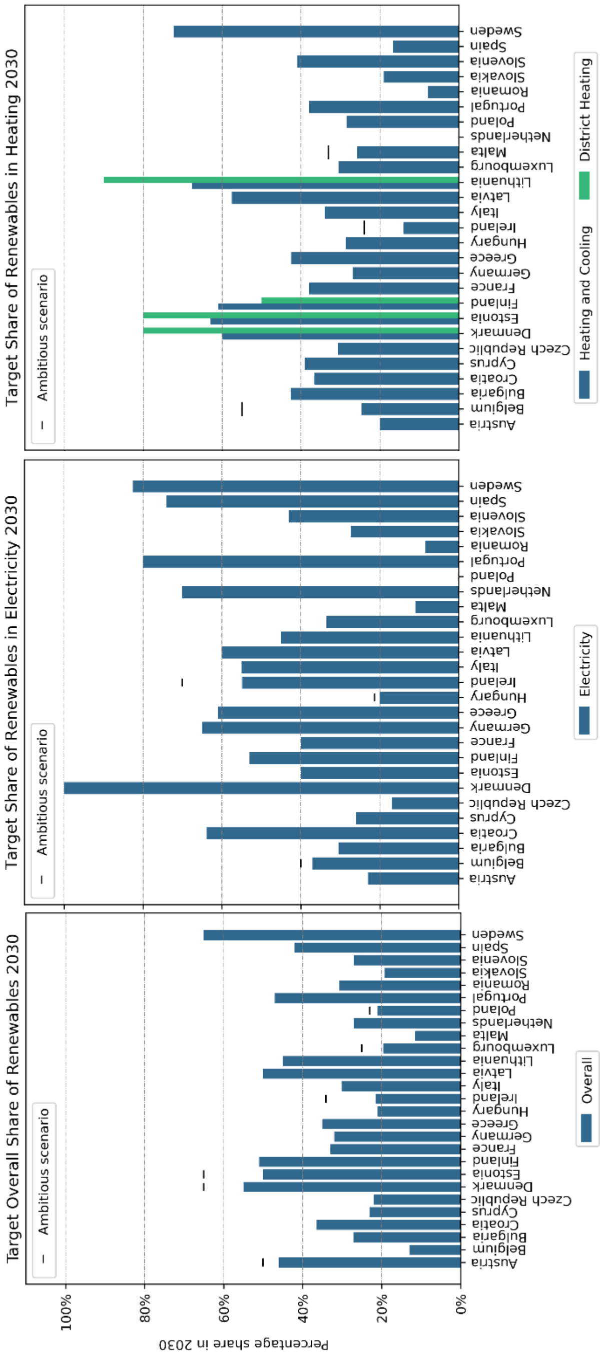


Figure 6.6 2030 renewable energy targets for overall energy supply, electricity and heating.
Countries with a 0% target means no target was found, not a target of 0% renewable energy (Bertelsen and Mathiesen (Submitted))

6.2.2 POLICIES AND MEASURES

Figure 6.7 below shows the number of measures documented in each of the nine identified sectors in the review of the NECPs. The sectors are *Society*, *Electricity*, *Energy Sector*, *Transport*, *Buildings*, *Fuels*, *Heating & Cooling*, *Industry* and *Agriculture.* Article 4 presents a comprehensive overview of the measures deployed within each of the nine sectors. Below, a summary of the measures deployed in the *Heating & Cooling*, *Buildings* and *Electricity* sectors is presented to investigate how the member states plan to develop their heating and cooling supply, building stock, and for comparison, electricity supply. These are selected due to their relevance for heat supply. The remaining measures are presented in Article 4.

Figure 6.7 also shows which NECP dimensions the measures in the different sector apply to. The NECPs cover five dimensions: *Decarbonisation, Energy Efficiency, Energy Security, Internal Energy Market* and *Research, Innovation and*

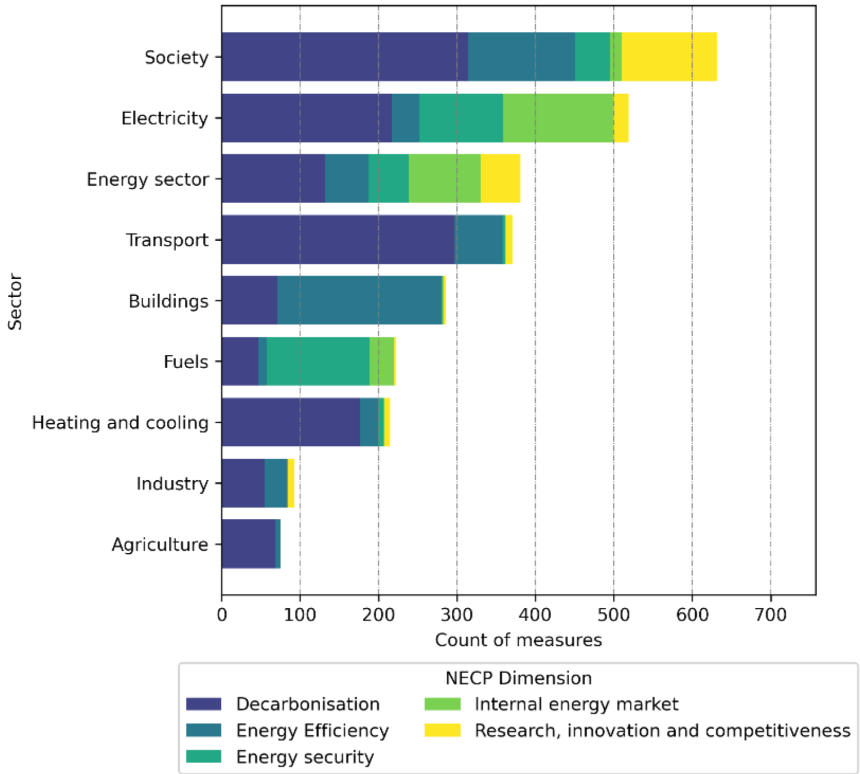


Figure 6.7 Number of measures in the NECP plans by sector and NECP dimension (Bertelsen and Mathiesen (Submitted)).

Competitiveness. The *Heating & Cooling* sector is made up almost entirely of measures from the *Decarbonisation* dimension. This highlights that the main focus of the measures is to integrate renewables into heating and cooling supply. For *Buildings*, the main dimension is *Energy Efficiency*, followed by *Decarbonisation.* This suggests that most member states are targeting end-use savings in the *Buildings* sector. Almost half of the *Electricity* sector is composed of measures from the *Decarbonisation* dimension, followed by measures from *Energy Efficiency* and *Research, Innovation and Competitiveness.*

While there is no direct correlation between the number of measures and their effectiveness, as discussed in 3, comparing the number of measures can still be interpreted as a sign of the relative importance assigned to the issue by the individual member states. In the 27 NECPs, over twice as many measures address the *Electricity* sector than the *Heating & Cooling* sector.

Measures for the Heating & Cooling sectors

Figure 6.8 shows the measures that address the *Heating & Cooling* sector. From the figure, it can be seen that most measures in the *Heating & Cooling* sector focus on district heating systems. A high proportion of these are *Financial & Fiscal, Information & Training* or *General*. As outlined in 4 above, significant investments are required to implement district heating infrastructure, which seems to be a focus judging by the high share of financial measures. The high share of *Information & Training* suggests that new knowledge, skills and expertise is required in the member states that are seeking to implement new district heating systems. The technology category *Broad Technological Focus* is the second most documented and covers measures with no particular targeted technology. Instead, it contains measures broadly applied to heat supply with no specific technological focus such as information campaigns, fiscal changes such as VAT rates for low-carbon heating equipment and direct public funding. With 19 documented measures, *Energy Efficiency* has significantly fewer measures than the two other categories, *District Heating* and *Broad Technological Focus*.

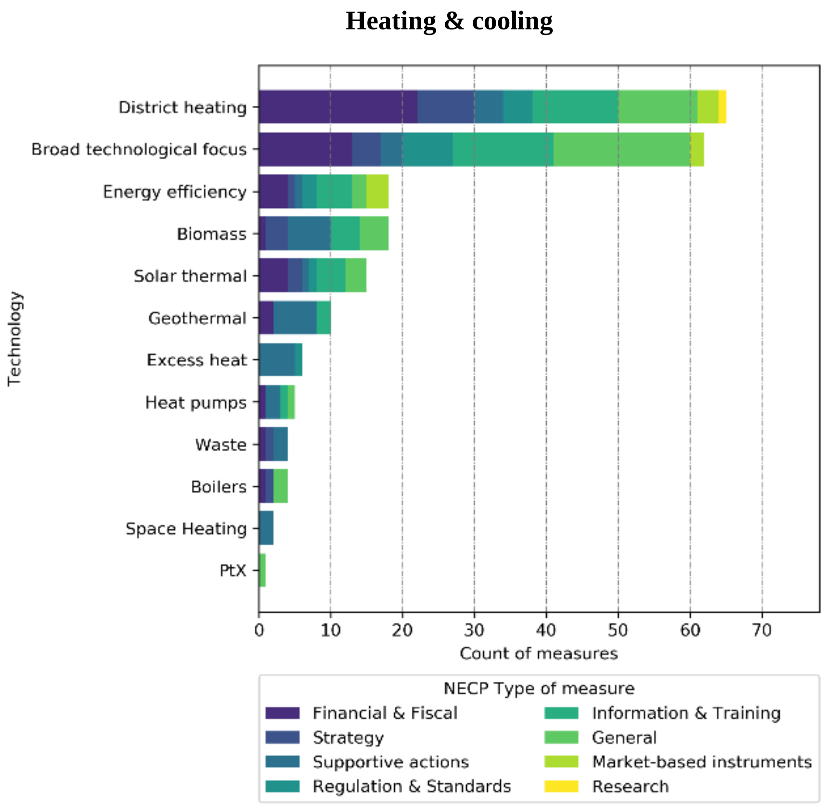


Figure 6.8 Measures in the heating & cooling sector by technology and type of measure (Bertelsen and Mathiesen (Submitted)).

The *Energy Efficiency* category also contains several *Information & Training* measures as well as *Financial & Fiscal* and *Market-Based Instruments.* Energy efficiency in the *Heating & Cooling* sector seems to be driven by aid schemes, replacement programs as well as workshops and monitoring and inspections of heating equipment. A number of technology-specific measures come after the three most addressed technological categories. *Biomass* and *Solar Thermal* could be used at the household level but also in district heating systems. *Geothermal* and *Excess heat* are exclusively available through district heating systems, as is heat from *Waste* or excess heat from *PtX* processes.

Measures for the Buildings sector

Figure 6.9 presents the measures within the *Buildings* sector. The two most documented technology categories, *Renovation* and *Energy Efficiency*, are closely related. While *Renovation* measures focus solely on improving the existing building stock, *Energy Efficiency* measures focus on decreasing energy consumption more broadly. The *Renovation* category comprises 36% *Financial & Fiscal* measures, constituting a large part of that category. Measures focus on public buildings through targets, goals and by using them as good examples, and private buildings through financial aid, changed taxation and VAT as well as financing options. A significant proportion of the *Energy Efficiency* category is comprised of *Information & Training*, *Financial & Fiscal* and *Strategy* measures. The *Energy Efficiency* category covers consultancy to investigate and identify energy savings for homeowners, businesses, municipalities and organisations, implement Energy Declarations on buildings and building standards including new low-consumption buildings and NZEB (Near Zero Energy Buildings) standards. Almost half of the measures in the *Broad Technological*

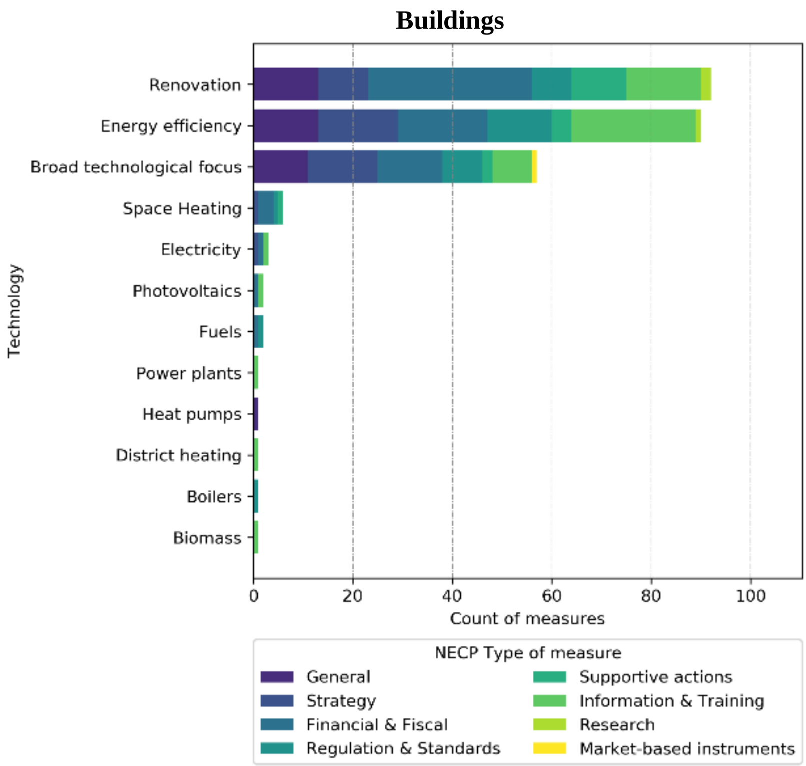


Figure 6.9 Measures in the buildings sector by technology and type of measure (Bertelsen and Mathiesen (Submitted))

Focus category are *Strategy* and *Financial & Fiscal* measures. The category includes long-term strategies for building development, financing plans, monitoring of areas for development, mandatory implementation of PV on public building rooftops and the identification of legal barriers. Similar with the measures in the *Heating & Cooling* sector, the remaining measures are technology-specific or are related to *Space Heating*.

Measures for Electricity supply

Figure 6.10 shows the measures documented in the *Electricity* sector. The *Broad Technological Focus* category is the most used, with more than twice as many measures as the next category. This category includes measures that generally apply to the development of electricity systems without a particular focus on a single technology. It includes identifying and planning areas for renewable electricity generation, the development of electricity markets and measures that encompass wind, solar, biomass and hydropower in different combinations and configurations.

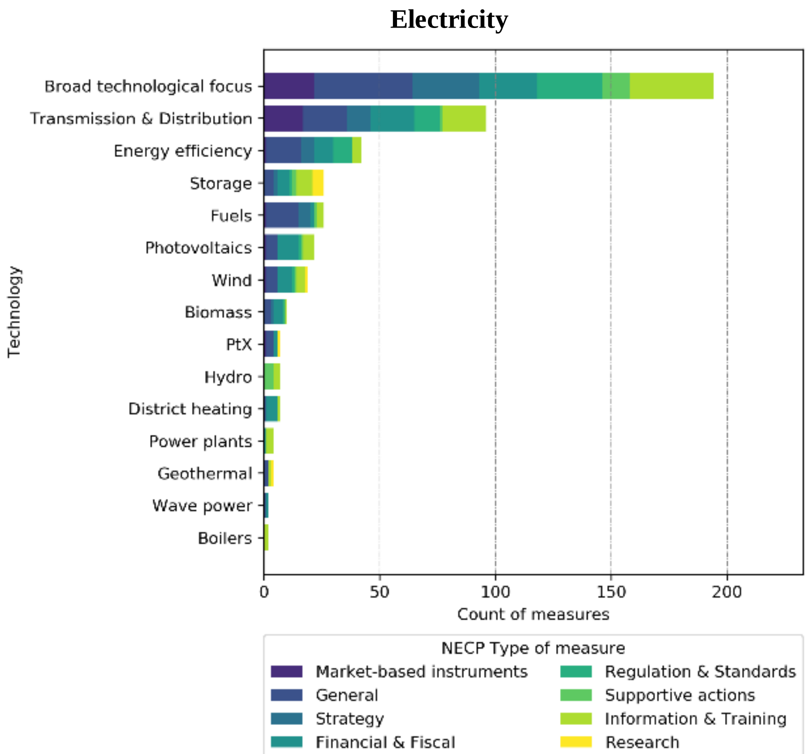


Figure 6.10 Measures in electricity sector by technology and type of measure (Bertelsen and Mathiesen (Submitted))

The *Transmission & Distribution* category covers measures for accommodating increased amounts of renewable, intermittent and distributed generation of electricity into electricity grids, adaptation to EU objectives for transmission capacity available for cross-border trading, avoiding bottleneck situations and cross-country cooperation between TSOs. The *Energy Efficiency* category includes smart meters, developing new more efficient materials for electricity grids, LED lighting and the replacement of old generators and transformer equipment. Most of the remaining categories are technology-specific, except for the *Fuels* category. *Storage* is the category with the highest number of measures focused on a specific technology, with measures including different types of electricity storage such as batteries as well as electric vehicles, smart meters and micro-grids.

EU-27 approaches to the Heating & Cooling, Buildings and Electricity sectors

The above summary of the measures documented in the *Heating & Cooling*, *Buildings* and *Electricity* sectors highlights different elements in the EU-27 countries' approaches to developing their energy systems towards 2030. The *Electricity* sector has both the highest renewable energy targets and the most measures. Most countries are, therefore, focused on decarbonising their electricity supply, while ambition in terms of heating and cooling remains limited despite high potential for renewable energy across the EU-27. The measures in the three sectors are also specific to their own supply sectors and without many sector-coupling measures. For example, measures in the *Buildings* sector are mostly focused on renovation and energy efficiency, while the *Electricity* and *Heating & Cooling* sectors mostly deal with supply technologies and infrastructural development. In addition, measures without a specific technological focus are widely used. This indicates that a governance where planners and public officials are reluctant to decide on specific technologies, and instead prefer to let actors decide in tenders, use markets designed for specific purposes or outlining strategies. Such approaches have been called *technology neutral*. However, they do still depend on specific infrastructure, designed tenders and that the use and purpose within a sector are specified.

6.3 THE STATE OF HEAT SUPPLY IN THE EU

In the EU27+UK, residential heating is largely based on fossil fuels with imports of fossil fuels and the share of biomass increasing. Several household boilers are non-condensing and much of the biomass combustion occurs in stoves. Several countries supply significant amounts of residential heat through large-scale infrastructure, mostly gas networks. District heating is the single most used type of heating in Denmark, Sweden and Finland, and natural gas is most widespread in Belgium, Germany, Hungary, Italy, Luxembourg, the Netherlands, Slovakia and the United Kingdom. The final energy consumption for residential heating and the average final energy consumption per residential m^2 decreased from 2000 to 2015. While the residential heat consumption decreased from 2000 to 2015, the supply situation improved slightly. The largest shift was from oil and coal to biomass and natural gas. Calculations of the impact of biomass on the climate range from a reduction in CO_2 emissions to emissions remaining at 1990 levels depending on how the impact is calculated. District heating and renewable energy did not increase during the period analysed.

However, the share of district heating will have to change if the number of measures in the NECPs are to have an impact. The review of the 27 NECPs has identified an interest in developing district heating systems. The countries with targets for renewable energy in district heating are also significantly more ambitious than countries that only report targets for their heating sector as a whole. The majority of measures within the *Buildings* sector are targeted at renovation and improving energy efficiency, which would continue the historical development from 2000 to 2015. While the NECPs contain elements targeted at a renewable and efficient heat supply, they are still mostly focused on the electricity sector. This reflects the increasingly central role electricity supply has been given in decarbonised energy supply in the future.

6.4 COUNTRIES IN DIFFERENT HEAT SUPPLY SITUATIONS

The results show that countries in the EU have different starting points from an infrastructural and technical perspective. As already outlined in 2, the socio-technical assemblages of existing technical infrastructure, heat supply methods as well as regulations, policies, knowledge and habits of consumers, have an influence on which pathways are considered feasible moving forward and which challenges are likely to be met. Based on Article 1 and Article 4, a discussion of the combined status of technical and policy approaches is presented in the follow sections, divided into three categories based on the most used types of heating infrastructures. Based on the countries' current technical and infrastructural situations, the following section discusses how countries with a high proportion of district heating, gas heating and individual heating can move forward towards decarbonising their heat supply. Each of the three types of heat supply has different potential and challenges. The discussion draws upon the descriptions and data presented in Article 1 and 4.

6.4.1 COUNTRIES WITH DISTRICT HEATING NETWORKS

As already argued above, district heating system show potentials for future low-carbon energy supply. Countries with existing district heating systems need to assess the current state of their infrastructure. This entails production, transmission, distribution and building level technologies. Some existing district heating systems are supplied by fossil fuels, use inefficient supply infrastructure and high supply and return temperatures, which both increases energy losses and hampers the introduction of renewable energy sources. Developers of existing district heating systems must reflect upon how they can improve and participate in an energy system transition to

Relation between current district heating share in heat supply and renewable energy targets for heating

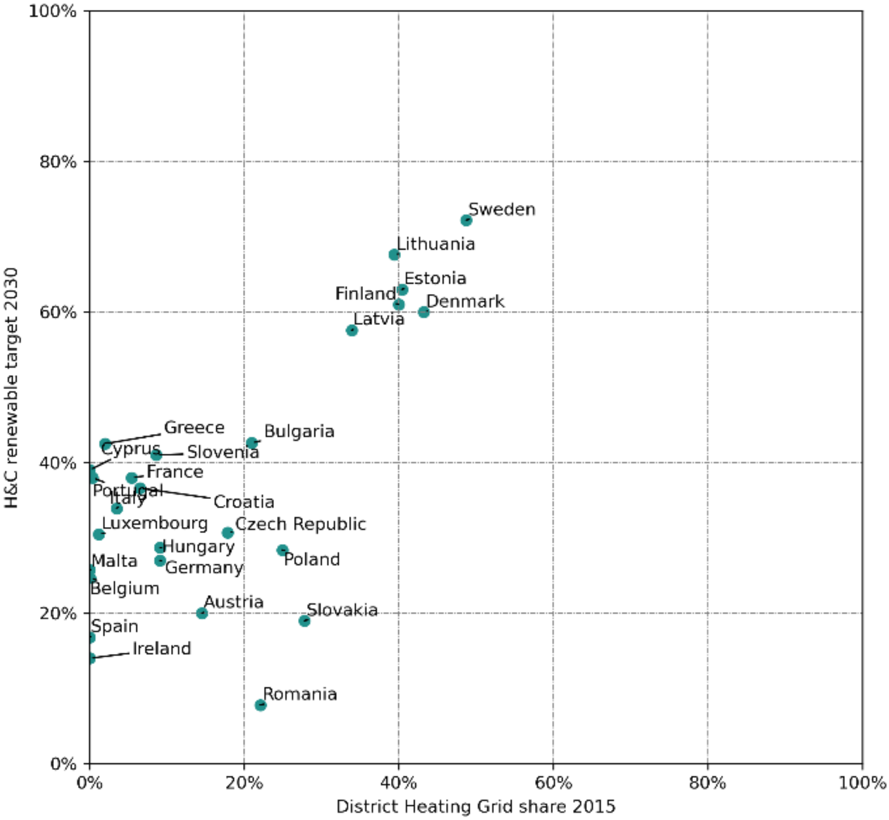


Figure 6.11 Relation between the district heating share in 2015 and the heating and cooling renewable target in 2030 for each country. The Netherlands and the the UK are not included due to missing heating and cooling target. Data from Bertelsen and Mathiesen (2020) and Bertelsen and Mathiesen (Submitted).

efficient and low-carbon supply. Although existing district heating infrastructure probably needs to be improved significantly, it still has potential to contribute to the overall decarbonisation of heating and energy supply. As shown in Figure 6.11**,** countries with a high share of district heating in their heat supply are more likely to have high renewable energy targets for their heating and cooling supply. Sweden, Lithuania, Estonia, Finland, Denmark and Latvia constitute a cluster with district heating supply shares of 34-48% of the total residential heat supply, as well as targets to achieve 50% renewable energy in the total heating and cooling energy consumption by 2030. The remaining countries in the EU-27 have lower ambitions for 2030 as well as a lower proportion of district heating today.

The NECP analysis also identified a high interest in developing district heating systems as part of a low-carbon heating and cooling strategy. Countries without existing district heating infrastructure are facing new developments of large-scale infrastructure, which constitutes the co-development of technical, organisational, institutional and expert dimensions. These challenges are discussed further below, but here it will suffice to say that it seems that countries with existing district heating infrastructure have higher ambitions in terms of the share of renewables in their heating and cooling supply. The main technical challenge will be to prepare the existing systems for increasing amounts of renewable energy in a way that contributes to a decarbonised energy system by 2050. In addition to the technical changes outlined in 4, countries or systems opting for low-temperature district heating will also need to manage and coordinate production through heat pumps, excess heat, geothermal or CHP. This will require attention to network access, business models for an increase in the number of producers and heat sources as well as ways of changing household heating equipment to the new supply standards. An example of this is the utilities in Denmark who are experimenting with taking ownership of household equipment, thereby gaining control of devices that were previously out of their reach (Caussarieu 2021).

6.4.2 COUNTRIES WITH GAS NETWORKS

Countries with existing gas networks for heat supply face difficult choices. Either gas networks need to be repurposed to use hydrogen, biogas or other green gasses or the gas infrastructure needs to be replaced by district heating grids or individual heating such as electric heat pumps or biomass boilers. Parts of the gas networks could then be repurposed to other areas where gas could remain useful, such as in flexible power plants (Rasmus Lund and Mathiesen 2015). Repurposing the existing gas infrastructure for heating requires massive amounts of hydrogen, biogas or other green gas production, and whether this is currently feasible, sustainable or cost-effective is doubtful (Korberg et al. 2021). On the other hand, the gas grids that are already in place are likely to remain due to their high sunk costs (see 7 below) and attempts by gas system actors to reframe the large-scale infrastructures to reframe their problem solving qualities to remain useful in the face of new societal challenges.

Figure 6.12 illustrates the relationship between the share of gas heating in residential heat consumption in 2015 and the targets for the share of renewable energy in heating and cooling in 2030. The figure does not include the two countries with the highest share of gas, the UK and the Netherlands, due to the absence of targets for renewable energy in heating and cooling in 2030. Of the remaining countries, below illustrates a relationship between a high current gas share and a low future renewable target for heating and cooling. This should be interpreted with some caution, but it illustrates that the countries with a higher share of gas are facing difficulties in outlining how to decarbonise their heating and cooling supply. This could be interpreted as existing gas

Relation between current gas share in heat supply and renewable energy targets for heating

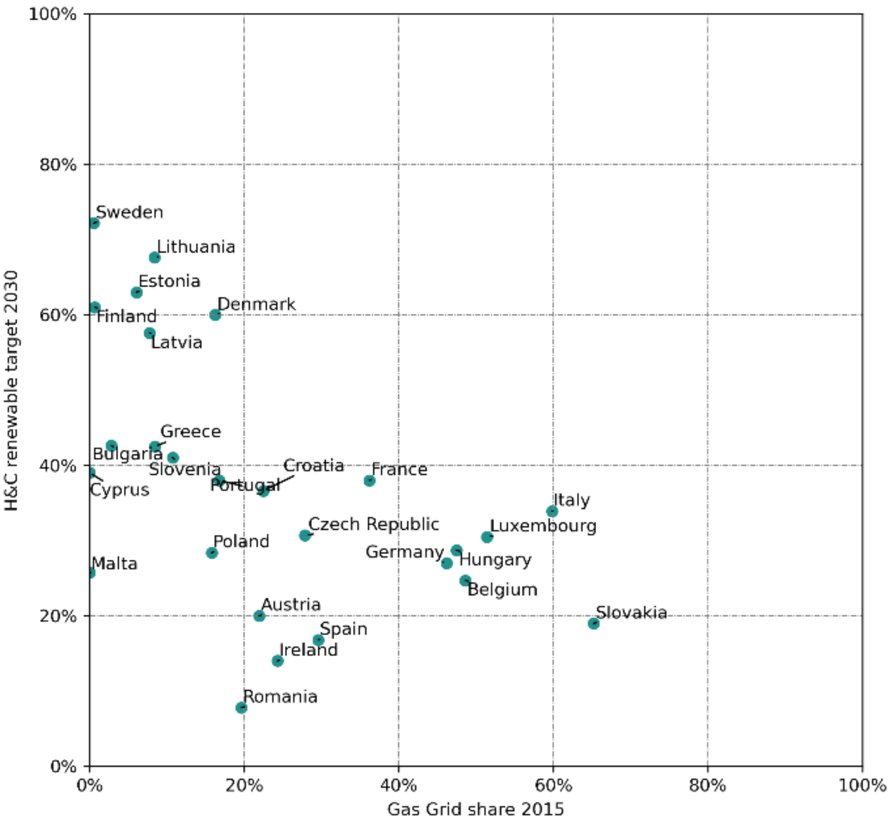


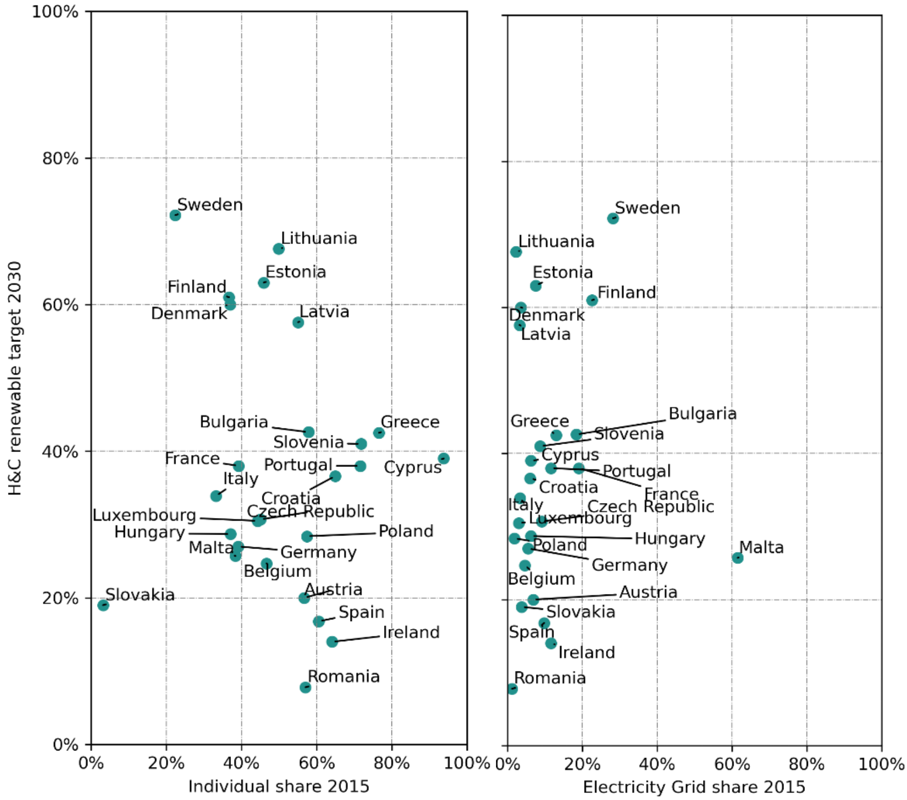
Figure 6.12 Relationship between the share of gas heating in 2015 and heating and cooling renewable target in 2030 for each country. The Netherlands and the the UK are not included due to the absense of a target for heating and cooling. Data from Bertelsen and Mathiesen (2020) and Bertelsen and Mathiesen (Submitted).

infrastructure representing a form of lock-in, thereby limiting options for decarbonisation.

While this thesis was being written, no examples of significant shifts in heat supply from one large-scale infrastructure to another were found, as would happen if switching from gas to district heating networks. Replacing one type of grid infrastructure with another is costly, especially if the existing gas networks still have much of their lifetimes remaining. As discussed below, a main driver of the expansion of large-scale heating infrastructure was the advantage of a stable supply, something that district heating grids can not deliver compared to gas supply to the same extent as they can compared to, for example, oil, coal or biomass heating.

Therefore, the future heat supply in areas with gas grids is uncertain. As shown in Article 2, existing infrastructure has changed societal meaning and problem solving abilities, and existing gas networks could again be reframed by mobilizing the

Relation between current individual share in heat supply and renewable energy targets for heating



A B

Figure 6.13 Relationship between the share of individual and electricity heating in 2015 and the targets for renewable energy in heating and cooling for 2030 for each country. The Netherlands and the UK are not included due to the absence of a target for heating and cooling Data from Bertelsen and Mathiesen (2020) and Bertelsen and Mathiesen (Submitted).

technical potentials of renewable and green gasses and the current positions of established gas companies. On the other hand, research shows the benefit of establishing district heating grids as they integrate heat sources that are otherwise hard to exploit and benefit sector integration.

6.4.3 COUNTRIES WITH INDIVIDUAL HEATING

Countries or areas that are mainly supplied with individual heating face challenges in choosing and establishing the necessary technologies to achieve an efficient and decarbonised heat supply. Individual heating technologies include oil, coal and biomass combustion in stoves and boilers. Electric heating using electric boilers or heat pumps is also included here. Drivers of change may include air pollution, a commitment to limit climate change or increase energy security, but potentially also to achieve a higher quality heat supply, although as these drivers depend on the specific supply situations, the list is non-exhaustive. Individual heating is usually characterised by a need for residents or consumers to organise or collect fuel, maintain and operate equipment, and make potentially high investments in new boilers and delivery systems when needed.

Figure 6.13 (A) below shows the relationship between individual heating, comprising coal, oil and biomass heating, and the renewable energy targets for heating and cooling consumption in 2030. Figure 6.13 (B) illustrates the same relationship for electric heating. Both figures illustrate no correlation between the share of individual heating and the future targets for renewable energy in heating and cooling supply. This shows that the current share of individual heating in residential heat supply does not reflect the decarbonisation ambitions of the EU-27 countries.

A central question facing areas with individual heating is whether to establish collective heat supply systems as district heating or continue with individual heating. From an optimal techno-economic perspective, this largely depends on the heat consumption density, e.g., how close heat consumers live to each other (Möller et al. 2019). As discussed in 4, district heating systems are usually only feasible if the heat consumption density is high enough to warrant investments in collective grids. Article 4 identifies significant interest in district heating systems within heating and cooling decarbonisation, and it could be expected that some of these measures will apply to the development of new district heating systems in areas currently supplied by individual heating. One significant challenge is the lack of existing organisations, regulation, know-how, financing and regulatory tools. These socio-technical assemblages are likely missing in regard to heating. Deciding whether to implement such large-scale supply infrastructure is an important decision, and decision-makers need to ensure that such solutions are relevant for future energy systems.

6.5 ESTABLISHING A NEW HEAT GOVERNANCE ASSEMBLAGE

This chapter has presented the main findings of Article 1 and Article 4 and discussed how these results impact future planning and the development of heat supply given different technological situations. The articles provide a description of the historical development and current condition of residential heat supply as well as how the EU-27 countries target and plan to develop their heat supply towards 2030. From the description, it is apparent that the residential heating sector is mainly supplied by fossil fuels, is characterised by increasing imports and dominated by gas grids and that there was no expansion in district heating or renewable energy from 1990 to 2015. Residential heat consumption has been decreasing since 2000. Looking forward, the EU-27 countries are mostly focusing on decarbonising their electricity supply and, in general, they seem to have relatively low ambitions regarding heat supply, although a significant share of measures addressing the heating and cooling sector are focused on district heating systems.

The analysis of the historical development reveals a new governance assemblage. As argued in 2, before an object can be steered, governed or changed, it is necessary to describe its properties and qualities. This section represents an initial attempt to define heat supply as a governance object by introducing it as a technical supply system comprising primary energy supply, supply infrastructure, final energy consumption, end-use technologies and the building stock. However, according to the analysis of current plans and targets in the NECP in Article 4, this is not how heat supply is currently addressed in measures and policies. Instead, heating is understood as supply, while energy efficiency is a question of building quality. The discussion of the connections between fuels, infrastructure and end-use as well as the different technological and infrastructural arrangements in the different countries highlight the scope, magnitude and potential of decarbonising heat supply and the challenges facing the process. The EU-27 countries are all in different situations, both from a technical point of view, but in terms of the governance assemblages that constitute their heat supply systems. These different starting points and conditions will influence future developments in heat supply.

7 TRANSITIONS AND CHANGES IN HEAT SUPPLY

This section presents the results from Articles 2 and 3 and discusses the main findings about the planning and implementation of technologies for heat supply. These two studies investigate cases of heat planning and transitions and identify elements in the successful implementation of new technologies.

Lessons from the planning and implementation of large-scale infrastructure in the UK, the Netherlands and Denmark are based on the findings in Article 2. This provides a historical account of how high market shares were reached with grid infrastructure for heat supply in the three countries. The next section builds on Article 3 and describes the case study of the planning and implementation of Thermal Energy Storage in Greater Copenhagen to illustrate how uncertainty was managed, how plans were used and the importance of stable governance assemblages to facilitate the implementation of new technological.

7.1 DEVELOPING LARGE-SCALE HEATING INFRASTRUCTURE IN DENMARK, THE UNITED KINGDOM AND THE NETHERLANDS

Article 2 investigates how the UK, the Netherlands and Denmark achieved high market shares of large-scale infrastructure in their heat supply. The UK and the Netherlands have a high share of natural gas in their residential heat supply, respectively 75% and 90% of the final energy consumption for residential heating (Bertelsen and Mathiesen 2020). In 2018, district heating infrastructure in Denmark supplied 90% of multifamily houses and 40% of single-family houses (Statistics Denmark 2020a).

None of the three transitions began as carefully planned projects as they were developed from pre-existing small-scale fragmented infrastructure. The three cases responded to changing conditions, global events and new political concerns. In the UK, gas supply was nationalized with the Gas Act of 1948, which unbeknownst at the time facilitated the reorganisation of the sector, which could then accommodate a large amount of natural gas when it was discovered in the North Sea in the 1960s. The Netherlands first considered their natural gas resource as abundant and cheap, but it was later reframed as a scarce energy resource that could help the country through the oil crisis of the 1980s. District heating in Denmark started out as collective systems, owned mainly by municipalities or consumers and supplying high-quality, cheap and stable heating. When Denmark was also hit by the oil crisis, the Danish Government responded by highlighting the energy efficiency potential of district heating, which was, therefore, repositioned as an efficient, oil-saving technology. Several different reasons for developing and maintaining this infrastructure were found throughout the period, which shows that the meaning and understanding of such large-scale infrastructure can change in line with the challenges they face.

Public ownership and available finance played a central role in the expansion of the large-scale infrastructure. Long-term investments, stable financing and business models that often involved expanding to large market shares instead of achieving high profits enabled reaching high market shares for the large-scale infrastructure. Low-profitable areas, often with low heat densities, were connected through profit sharing mechanisms from more profitable areas. In the UK, gas supply was nationalised and organised into 12 Area Boards and the Gas Council, which managed the gas system until natural gas became widely used. The transition from manufactured gas to natural gas also meant organisational changes, whereby the 12 Area Boards were dissolved and management was centralised in British Gas. While the UK relied on a gas sector that was entirely publicly owned, public and private actors cooperated in the Netherlands to develop the gas networks. Private companies mainly managed the production and extraction of gas, while public organisations built and maintained gas networks and distributed gas to consumers. In Denmark, district heating systems were mostly publicly owned, either by municipalities or by the consumers themselves. The ownership remained tied to the system infrastructure, in the sense that a municipality or cooperative would own the specific district heating system supplying the area. In all three cases, some sort of public ownership was involved. The specific configurations differ between the cases, ranging from national ownership of production, distribution and infrastructure in the UK, public-private partnerships owning the infrastructure in the Netherlands to municipal or consumer ownership of district heating systems in Denmark.

Several different actors and organisations were present in the three heating transitions. National, regional and municipal governments and authorities as well as private companies, citizens and utilities were all engaged in planning and maintaining the systems. Existing organisations and companies were important in the three case studies as they utilised their positions to implement novel infrastructure. In the UK, existing gas manufacturing and distribution companies were nationalised and merged under the Area Boards. Later, the infrastructural systems were used to distribute natural gas from the North Sea. In Denmark, the district heating supply companies established before (and after) the oil crisis, came to serve an important role in limiting oil consumption. In the Netherlands, the DSM became a central actor in the new gas regime with expertise in coal mining.

An example of *governing at a distance* (Miller and Rose 2008) is the Danish Heat Supply Act, which stipulates that municipalities should make heat plans for their areas by collecting statistics and analysing potential. With this assemblage of regulations, standards and expertise, the Danish government created mandatory heat planning processes, which also resulted in the establishment of socio-economic planning practices inscribed in the law. Making heat plans by following methodologies and processes outlined by the Danish Energy Agency and Ministry ensured that the municipalities in charge had the flexibility to accommodate the plans to their specific circumstances while overall national goals were pursued. In the UK, the *Clean Air Act* specified which heat supply methods were free of pollution and could be used in designated *black areas* suffering from poor air quality. The UK gas supply was also regulated according to the principles of serving a public purpose and operating efficiently with break-even principles.

Shifting assemblages for large-scale infrastructures

The large-scale infrastructure for heat supply analysed in these three case studies did not inherently contain specific technological qualities. Rather, these qualities and problem-solving capacity were constantly reframed and emerged based on the situations that they were placed in. The aim of the large-scale infrastructure changed in the face of the oil crisis as did the aim and qualities of the UK's gas grids once infrastructure had been nationalised.

While the problem-solving capacity of large-scale infrastructure changed, it did not occur as the result of carefully planned transitions. These qualities emerged due to engagements in uncertain situations. An example is the British gas supply system before the discovery of natural gas in the North Sea, where several pathways of gas supply were explored. At the time, future gas supply could have been manufactured with the Lurgi Process, imported by ship from Algeria or the US or via pipelines from the Netherlands. Likewise, the Danish district heating systems only became the subject of national regulation with the oil crisis, which they then became central in mitigating.

Several different aspects proved important in realising high market shares of large-scale infrastructure in heat supply. Societal drivers pushed the infrastructural developments forward. Ownership and business models that allowed expansion and long-term investments were deployed with cooperation between public and private actors. Coordination between actors was maintained by assemblages of diverse centres of agency facilitating the adjustment to local conditions while overall national objectives were maintained. This meant that the large-scale infrastructure could supply high-quality cost-effective heating, as well as increase energy efficiency and energy security, although each of these factors were important for different actors. An important finding is, therefore, the flexible role, understanding and purpose of infrastructure through the three transitions. Although large-scale infrastructure is obdurate, locked-in and has a long lifetime, its societal problem-solving capacity changed reflexively according to the challenges encountered.

7.2 THERMAL ENERGY STORAGE IN COPENHAGEN: COORDINATION IN UNCERTAIN MULTI-STAKEHOLDER ENVIRONMENTS

Article 3 shifts the attention from a historical account to the development of a specific project *in medias res*, e.g., the events were investigated as they occurred. The study followed the making of a thermal energy storage (TES) in Copenhagen by focusing on the use of energy scenarios, strategies and visions by actors navigating uncertain situations of sensemaking. It is a case of actors going from long-term imaginaries of a decarbonised energy system towards a specific investment in a technology through negotiations, deliberations and uncertainties.

The article highlights the role of epistemic devices such as plans in a planning process and discusses what they do and do not do. Epistemic devices are understood as objects that produce, translate and circulate knowledge such as the energy models producing results as well as the reports, plans, strategic documents, etc., into which results and findings are inscribed in order for them to be able to circulate. Epistemic devices were deployed in situations of uncertainty in which the actors needed to make sense of the conditions and options for action. These situations could be interpreted as *wicked* (Cajot et al. 2015) as they had multiple solutions, actors, interests and ill-defined problem areas. Three successive instances of uncertainty moved the process forward by simultaneously closing down and opening up uncertainties. These three instances are discussed below in Figure 7.1.

The first instance of uncertainty concerned how the existing district heating system could exist in a future decarbonised energy system. Leveraging an already existing professional network called Heat Plan Copenhagen (HPC), two transmission system operators and a utility company used energy consultants and energy system simulations to enact a future scenario that described how their existing plants, infrastructure and investments could take part in a low-carbon energy supply. One result from this epistemic work highlighted that increasing TES capacity would decrease the need for fossil fuel peak boiler capacity and allow the CHP plants to operate more efficiently and integrate more wind power in the energy system.

The second uncertainty and process of sensemaking came from the identification of the TES as one of the central means of decarbonising the Greater Copenhagen district heating system. Having identified the TES as a central technology in a future energy system configuration, the question of how it should be used and operated arose. Again, energy plans solicited by a TSO and a utility were deployed in response to the uncertainty. The results showed that, given the model assumptions, parameters and forecasts, the TES was most profitable as a *system* investment operating on a *short-term* timescale. Framing the TES as a system technology meant that using it not only for the benefit of one actor, but for the entire system, would result in collectively greater benefits. The short-term operation defined that instead of storing energy

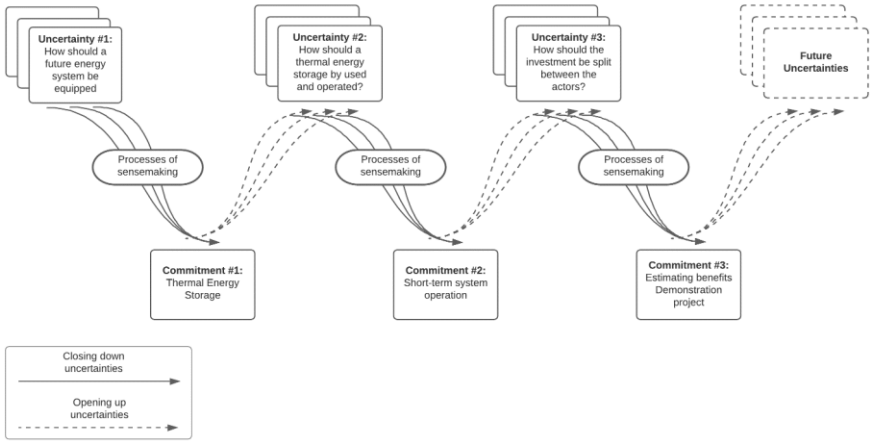


Figure 7.1 The three instances of closing down and opening up controversies and uncertainties during the process (Bertelsen, Caussarieu, et al. 2021).

seasonally from the low-consumption period during the summer to the high-consumption period of winter, the TES would provide a greater benefit if it were used on a daily and weekly basis. This would allow CHP plants to optimise their operation according to electricity prices.

The third uncertainty and sensemaking process emerged out of the decision that the TES should be used as a *system* storage. Calculating the benefits for all district heating actors in Greater Copenhagen meant that they also had to share the investment costs according to their expected benefits. While the investment costs were relatively well known and the combined benefits for the system had been estimated, it proved difficult to translate this figure into individual costs and benefits for the specific actors in a plausible way. Instead of being able to simply translate the model results into a business model, the energy system calculations were used as inputs and as the basis for negotiating how the costs and benefits should be divided between the actors. Another qualification, the framing of the TES as a demonstration project, also shifted the actors' expectations about the new technology. The demonstration project introduced a degree of flexibility into the financial expectations of the actors, which meant that they accepted a higher level of uncertainty in terms of economic returns and a developmental aspect of the business case.

Challenges such as these, which are characterised by different interpretations, viewpoints and with no clear problem formulation, have been described as *wicked* (Cajot et al. 2015). Nevertheless, the *wicked* problem was solved, not through identifying the right solutions, but through gradually and tentatively navigating one uncertainty at a time through collaborative efforts.

7.2.1 PROCESSES OF OPENING UP AND CLOSING DOWN

The findings of the analysis highlight several features of establishing novel low-carbon technologies. First, several framings and understandings of the TES were present throughout the case, all of them emerging from the scattered actor situations. By asking the question of how the energy supply of the Greater Copenhagen district heating system could be decarbonised, the TES was brought into being as a technology of *sector-integration* and *peak-load reduction*. By investigating how it should be operated, several strategies were proposed and closed down by epistemic model work, which identified the storage as *short-term* and *seasonal* as well as *system infrastructure.* None of these categories, understandings or framings were well planned or known from the beginning, but they became properties emerging from processes of sensemaking that closed down and opened up uncertainties. This continuous process of opening up and closing down uncertainties, as illustrated in Figure 7.1, was central in moving the innovation process forward as qualities were established and decided upon.

The epistemic devices became central in closing down uncertainties of the actors. In most of the instances analysed here, they convincingly aided and enabled sensemaking processes. This was achieved as the epistemic devices were based on specific questions and challenges such as how existing CHP plants could exist in a low-carbon energy system or how the TES should be operated. But analysts also saw the TES from a system perspective: how the technology would interact with the whole Greater Copenhagen district heating system, what the impact it would have on electricity production, and how it would benefit different actors. In this way, the epistemic devices brought the TES into being in particular and relevant ways for all the central stakeholders and decision makers. The epistemic devices were effective in that they helped define the qualities of the TES and convince actors and stakeholders into supporting these framings. An important aspect was that the relevant actors were included in energy projections of the future and it was often suggested that the TES would solve their concerns and challenges. The TES was positioned to improve CHP operation by allowing flexible production, which benefitted the plant owners, while it also allowed a reduction in peak production, which benefitted the TSOs.

The TES investment case illustrates the difficulty of organising and coordinating actors with scattered agency (Iuel-Stissing et al. 2020). All the stakeholders attempted to make sense of the district heating systems and the potential of the TES from their own particular perspective within the system. There were no privileged outside positions from which actors could know and define the course of action. Nevertheless, attempts at creating common narratives, problem definitions and mutual approaches helped to coordinate action. These attempts, inscribed in plans and scenarios, were used to produce common approaches to uncertain situations.

While the epistemic models were important tools, they did not work alone as they formed part of an assemblage in which long-term cooperation between the plant owners, utilities, TSOs and regulatory conditions enabled stable and long-term investments. This heat planning assemblage benefitted from these factors: long-term cooperation promoted trust between the actors, the heat planning regulation resulted in a common planning language, while the existing infrastructure provided a basis for common approaches as the actors were tied together through the district heating grids and pipes. These aspects represent some of the factors that enabled the successful realisation of the TES as a common infrastructure.

7.3 STABLE GOVERNANCE ASSEMBLAGES

Both Article 2 and Article 3 examine heat transitions in which the planned changes were achieved. They can be described as successful heat planning cases, at least seen from an ex-post perspective. The Greater Copenhagen district heating actors decided to invest in the thermal storage, the UK and the Netherlands built gas grids and Danish municipalities and communities built district heating grids. However, what the cases also show is that the goals were not defined before the transitions started but were rather emergent and appeared during the development. The use and operation of the thermal storage might seem obvious when examining it in hindsight, but it was a source of great controversy during the process. Similarly, the gas and district heating grids gradually shifted from one type of supply among many to become the dominant design. While the case studies show how planning and investments succeeded in implementing new technologies, this could have gone differently and they should not be understood as optimal designs, but instead as the emergent products of the specific socio-technical conditions at the time. This also highlights a trait about transitions: while large-scale transitions become visible in hindsight, they depend on everyday changes, one step at a time.

2 introduced the notion of assemblages, which becomes useful here. The term highlights the loose and fluid connections between the different elements, actors and devices that play a part in rendering their objects stable, knowable and governable.

The results section above has already elaborated on how the societal purpose of the different gas and district heating infrastructure changed through the period covered. Gas in the Netherlands changed from being an abundant to a scarce resource following the oil crisis, and the understanding of gas in the UK changed with the governance tools used to evaluate progress and performance. While the materiality of this infrastructure is extremely obdurate, investment heavy and last decades, their use, purpose and societal problem solving capacity were fluid and ever subject to change. They were *framings* based on an assemblage of knowledge equipment and societal challenges, and when these changed, the purpose and particular use of such infrastructure also changed. As another example and as outlined in 4, district heating is currently undergoing a shift to taking part in sector-coupling and producing energy system flexibility. District heating, which was considered an energy efficiency measure in the 1970s and 1980s, is becoming a way of balancing energy systems based on large amounts of fluctuating renewable electricity.

The fact that the transitions in Articles 2 and 3 are still successful is because they facilitated the materialisation of the technologies and infrastructure. The governance assemblages transitioned from strategies and plans to specific investments. The following section discusses central elements of how this occurred in the cases covered based on the four categories from Article 2, i.e., Drivers and Technological Qualities, Ownership and Financing, Actors and Coordination, and Policy and Governance. In relation to these four categories, the section analyses the key elements that make a governance assemblage capable of successfully implementing technologies and infrastructure under uncertainty.

7.3.1 DRIVERS AND TECHNOLOGICAL QUALITIES

Both the historical account of the expansion of infrastructure and the implementation of thermal energy storage relied on pre-existing drivers that pushed the projects forward. In Greater Copenhagen, it was a combination of national and municipal decarbonisation goals, which together increased interest in thermal energy storage. A main challenge facing the actors was how their existing plants and technologies could remain useful in a future low-carbon energy system, and this became the main driver for exploring and subsequently investing in thermal energy storage. The drivers for implementing large-scale infrastructure for heat supply were also central in expanding the infrastructure. The oil crisis drove much expansion in Denmark and the Netherlands by positioning the infrastructure as a solution to the new societal challenge of energy scarcity.

It was necessary to define the technological qualities in all these cases. Central questions related to what the technologies in question were able to do and how they could help solve the problems at hand. This is discussed in depth in Article 3, which analyses the thermal energy storage investment case. Here the technological qualities were debated, analysed and discussed during negotiations about tools, devices and business models. While it was not possible to investigate how the different infrastructural framings and the capacity for problem solving emerged, the historical account still demonstrates how these changed during the periods analysed.

Therefore, a successful governance assemblage must define the challenges a given technology should help to solve and outline the specific qualities of the technology at hand. As argued in the 2, this is no easy task as it depends on the convergence of the assemblage. In highly convergent networks, there is a common understanding of the used tools, devices and expertise, while in less convergent networks, no privileged knowledge or expertise is present. It is, therefore, difficult to establish common and shared understandings of technologies under scattered agencies. It is important to produce common understandings and collective framings, especially for large-scale infrastructure, which represents a collective solution that spans many users and requires significant investment. In highly convergent networks/assemblages, a knowledge infrastructure is often in place for the assessment of the infrastructure. In Denmark, there are guidelines for how to assess investments in district heating systems from a socio-economic perspective. These must be followed by everyone that wants to invest, expand or implement district heating. If such common knowledge tools are lacking, it is difficult to establish a common ground that can qualify technologies.

7.3.2 OWNERSHIP AND FINANCING

Article 2 identified no private or single owner investments in gas or district heating grids in the three case countries. Financing with long time horizons was also central in building energy infrastructure. Public authorities and organisations played a central role in financing, and as owners of the grid infrastructure, they provided stability and certainty for the development. It is important to distinguish between the grid infrastructure itself and the production technologies, whether they be natural gas extraction or district heating production units. In all cases, the grids depended on public financial support. Production units can then be built and operated based on a number of different financial schemes such as the True Cost principle for district heating in Denmark, cost-effectiveness in the UK or public-private partnerships for gas extraction in the Netherlands. Similarly, in the electricity sector, a number of different mechanisms structure and facilitate investments in electricity production such as feed-in-tariffs, tenders, capacity payments, or other market devices and designs. All these production units depend on a central grid infrastructure to transmit and distribute electricity.

Article 3 highlights the complexities arising from multi-stakeholder investments in new energy technologies. It is not certain that all energy storage units will be subject to the same challenges but increasing the focus on sector-integration will most likely result in increasingly complex ownership structures across sectors. District heating systems are technically capable of exploiting waste heat from several sources including new types such as data centres, Power-to-X, or even metro-systems and supermarkets (Nielsen et al. 2020). New types of business models and financing for these projects have to be managed.

Article 2 and Article 3 both illustrate the scattered agencies that must coordinate new investments in future energy systems. The point argued above about the importance of producing collective understandings of new technologies becomes increasingly important here, as actors and stakeholders will have to agree and cooperate on a number of new investments. Article 3 illustrates that diverging perceptions of technology do not necessarily represent a barrier to common investments as long as there is a common purpose in the form of an overall target. Furthermore, it is central that public authorities such as municipalities, energy agencies, ministries and governments engage in the transitions. Based on the analysis in Article 2, it is especially important that public organisations become involved in the collective and large-scale grid infrastructure that is needed for energy transmission and distribution. As plans and strategies outlining future decarbonised energy systems continue to advocate sector coupling and more integrated systems, it is likely that more complex ownership and coordination issues will arise.

7.3.3 ACTORS AND COORDINATION

Coordination and cooperation among actors have already been highlighted as central elements in the two sections above on Drivers & Technological Qualities and Ownership & Financing. Drawing on the content of the 2, the convergence of a system depends on common references, the ability of actors to cooperate and coordinate different tasks. If no frame of reference is established, it can be difficult to coordinate actions. Most actors in the two articles also referred to common goals, while they had their own independent objectives. For example, the actors in Greater Copenhagen agreed on the broad target of decarbonising heat supply, and the Danish municipalities participated in heat planning to improve energy efficiency in the 1980s. The TSOs, utilities and companies could then have their own additional motives while subscribing to these common overall objectives. For example, the utilities in Greater Copenhagen have to maintain the security of supply and ensure stable grid temperatures and low prices, while the CHP plants make a profit on their electricity production and sell heat according to the True Cost principle. These independent objectives did not conflict with the broader societal goal of achieving a low-carbon energy system.

As shown in both Article 2 and Article 3, incumbent and established actors drove the main changes and transitions. Some accounts of theoretical transition highlight incumbent actors as sources of path-dependency and lock-in (see for example Geels 2002). However, in the case studies presented here, the incumbent actors participated in the ongoing transitions. This may be because most of the actors did not really have a choice in that if they did not participate in the energy transitions, they would simply cease to be relevant in the energy system. As discussed in the two articles, there was considerable momentum behind the transitions, and any actors opposing this development would have risked their equipment and infrastructure becoming obsolete. It probably would not have been possible for a CHP plant in Greater Copenhagen to oppose the decarbonisation measures in the face of such significant support for the low-carbon transition. Nevertheless, CHP plants and other district heating actors participated with their existing investments, tools, knowledge and skills to exploit the infrastructure that was already in place.

A central question emerges here, which is what role the gas networks and their owners and operators will play in future energy systems. Will gas transmission and distribution systems be able to reframe themselves and participate in a low-carbon energy supply or will they become redundant? Gas industry stakeholders will probably call for a central role for gas and point at hydrogen, biogas and e-fuels as potential fuels for future energy supply.

7.3.4 POLICY AND GOVERNANCE

Articles 2 and 3 show that there was no independent local planning, but instead assemblages of regulations, actors, knowledge and expectations that enabled stakeholders to act. Governance tools, mandatory analyses and assessments as well as rules about calculations and assumptions constitute these planning assemblages. All of these combined with the many stakeholders, e.g., the municipalities, utilities, energy supply companies, citizens, etc., participated in the process. While the technologies were implemented locally in all the cases, they cannot be defined as local energy transitions as this ignores many important factors that enabled the changes. Many of the central policies and governance tools such as the mandatory socio-economic calculations in Denmark, the concept of cost-effectiveness in the UK or the Danish government's decarbonisation goals were formulated at the national level. These governance tools made it mandatory for "local" actors to investigate the feasibility of the technologies based on very specific assumptions and calculation methods. This governance approach is also included in the NECP plans, which demand that the EU-27 countries assess the potential for renewable energy and energy efficiency. The process of conducting these assessments produces and brings the alternatives and choices into being. It seems that by promoting "choice production", this governance at a distance of is effective at raising the responsible actors' awareness of different options and pathways.

The cases demonstrate that particular framings and not holistic understandings of technologies and infrastructure shaped the developments. The governance assemblages rendered particular perspectives useful and made it possible to steer the developments in line with these points of view.

7.4 CONDITIONS FOR CONVERGENT GOVERNANCE ASSEMBLAGES

In 2, I presented the argument that in order to agree on controversies and uncertainties, it is important to share a common understanding of the challenge. Callon (1995) asserts that in order to discuss the validity of the findings of experiments, researchers need to agree on the validity of the underlying theories and tools used to produce and interpret the experiment. For example, if not using similar calculation tools, assumptions and methodologies, it can be difficult to reach similar conclusions. A similar point is made in Article 3 concerning the thermal energy storage. For the different stakeholders in Greater Copenhagen to be able to progress from the challenge of how to participate in a low-carbon energy system to agreeing on a specific business model for the investment in thermal energy storage, a range of agreements had to be made along the way. *Closing down* an uncertainty or controversy allowed the actors to take a step forward and, based on the new agreement, deal with further uncertainties.

When the technologies in question became known through calculations, either as cost-effective measures, energy-efficiency improvements or as a short-term system infrastructure component, it closed down uncertainties and produced the knowledge necessary to move forward. Building on Smith and Stirling's governance on the *inside or outside* (2007), much of the planning and governance that enabled the construction of large-scale infrastructure in the Netherlands, the UK and Denmark, including the thermal energy storage, relied on framing and qualifying the technical objects as discrete and knowable objects, which could then be governed.

Therefore, a central finding that emerges from these observations is the importance of being able to qualify and frame technologies as discrete, knowable objects that can be observed from an outside position. As previously argued, a certain technology cannot be known in its entirety. Knowing will always be a particular framing, bringing certain qualities into being while obscuring others. Nevertheless, it is precisely by agreeing about which qualities count, which framings should be used and which epistemic tools, expertise and knowledge should bring the technology into being that allows it to be governed. This again highlights the process of closing down and opening up (Stirling 2005) that also shaped the process described in Article 3. As Farías and Blok (2016) are concerned with *"how shared urban realities are made and remade in various contested practices"*, the findings of Article 3 highlight the necessity of creating common understandings of messy realities while simultaneously being reflexively aware of the ever-changing conditions on which such realities are based.

Low-carbon heating transitions require tools, knowledge and expertise to bring into being the alternative technologies that can pave the way for a low-carbon society. This knowledge creation demands that other stakeholders engage with, understand, critique and promote the arguments, findings and facts. More importantly, governance tools and public regulation face similar challenges. These governance devices also depend on the specific framings of their governance objects, whereby particular qualities are measured and others left out. The way in which the governance devices are measured and evaluated helps to render them feasible, understandable and amenable to intervention.

A number of features of stable governance assemblages have been identified . There is an inherent conflict between objectively knowing objects with shared and accepted qualities and then the specific, partial and situated positions of actors scattered across the assemblages. A governance assemblage for low-carbon heat supply needs to accommodate different agendas while providing an overall common approach, which does not need to be interpreted in the same way but should provide a common sense of direction.

While highlighting the multiple understandings of technology, it is important to discuss one particular aspect of energy systems that allows production to be connected with supply: the transmission and distribution grids. Such central infrastructure is often governed by public organisations, which are responsible for its operation, maintenance, development and for implementing the rules that dictate which additional actors can access and use it. Electricity grid frequencies, district heating grid temperatures and gas grid pressure are some of the attributes that must be followed by actors. When in place, these attributes are also agents of convergence although they might not produce shared aims and understandings, they result in the implementation of common rules, entry requirements and system responsibilities.

Therefore, an interconnected and sector-coupled energy system will probably have *more* actors, roles and perspectives rather than *fewer* all-encompassing roles. Article 3 illustrated the difficulty involved in coordinating efforts for a single technology, but also how diverse the benefits were for the actors involved. New roles are already emerging in the electricity sector such as the aggregator, who seeks to combine the flexibility offered by individual heat pumps and electric vehicles. District heating imaginaries arguing for using heat pumps, excess heat, geothermal, solar thermal and unconventional heat sources from metro systems or supermarkets also face the entrance of multiple new agents and roles managing these new technologies. How these assemblages will be organised, only time will tell, but it is hard to imagine the emergence of a shared logic across these increasingly complex systems.

8 CONCLUSIONS

The research question posed in this Ph.D. thesis is as follows:

> What are the current and historical conditions of EU´s heat supply and how can heat planning and governance inform planners and policy makers on navigating uncertainty towards a low-carbon heating future?

The four articles that constitute this thesis contribute to answering parts of this question, while the thesis itself aims to bring each of the four articles together to answer the research question posed here. This thesis also reflects on the findings and tries to advance the arguments made in the four articles.

Article 1 addresses the technical historical development and current situation of heat supply in the EU-27+UK countries. Article 4 examines the current NECP plans implemented in the EU-27 countries to develop their energy supply in general and specifically their heat supply towards 2030. Article 2 explores the historical conditions for building and expanding large-scale infrastructure for heating and examines how planners and policy makers navigate this development. Article 3 puts uncertainty at the centre of the analysis and examines the development of a thermal energy storage by following the actions of those involved.

The specific conclusions of the articles are presented above in 6 and 7 as well as in the articles themselves. This chapter, therefore, discusses how they contribute to answering the overall research question of this thesis.

8.1 CURRENT AND HISTORICAL HEAT SUPPLY CONDITIONS

The findings indicate that historically heat supply has been sparsely addressed in energy planning and governance. Several countries mostly rely on individual heating such as boilers and stoves, which do not require significant coordinated planning. Article 2 illustrates that although the UK and the Netherlands expanded large-scale collective gas grids so that they represent a high market share of residential heating, this was also the product of fuel policy, domestic resources and energy efficiency improvements. The expansion of district heating in Denmark was also driven by energy efficiency measures, which indicates that an independent object such as *heat planning and governance* is not widespread across the EU-27+UK countries. According to the results of this thesis, what comes closest to specifically governing heat supply is probably the Danish heat supply act, which specifically mandates municipalities to make plans for heat supply. As this thesis has not investigated all the countries in the EU and their approaches to heat regulations and governance, this argument comes with some limitations. Nevertheless, there is some evidence that heating has often been regulated as part of either fuel, energy efficiency or building regulations and policies and not specifically. District heating imaginaries argue that there are benefits across all of these factors that might be hard to measure and render tangible as governance objects through sporadic attempts at regulation.

There is a need for concerted action to limit CO_2 emissions from heat consumption. Residential heat consumption in the EU is mostly fuelled by fossil fuels. While biomass consumption is increasing, there was no increase in the share of renewable energy in heating from 1990 to 2015. In addition to limiting CO_2 emissions from heat supply, there are a number of other reasons for reducing fossil fuel consumption in heat supply including air pollution, energy security or energy access.

The National Energy and Climate Plans (NECPs) set out the countries' targets, goals and policies for developing their energy systems. The targets are high for electricity supply but lack ambition for heat supply. The analysis of the NECPs also highlights that heat decarbonisation targets are on the same level as the overall climate targets, illustrating that most countries are not particularly ambitious in terms of decarbonising heat supply. Only the countries with district heating systems have ambitious goals, which illustrates how technological infrastructural systems are connected with policy targets. While gas supply and individual heating dominate the current technical heat supply situation, there is an interest in increasing the share of district heating systems for heat supply. District heating has received the most attention in the form of regulation within the heating and cooling sector.

Several countries in the EU appear to be interested in significantly expanding their district heating systems. Countries with existing district heating systems can use the current organisation and infrastructure for further development. These countries will need to accelerate a shift away from fossil fuels, in the form of the direct production of heat only or CHP plants and other excess heat resources. Old transmission and distribution grids will need to be refurbished while new grids may potentially be needed to connect new heat sources with existing and new demand. Countries with a high share of gas heating need to choose between their existing large-scale infrastructure, constructing new ones in the form of district heating or shifting to individual heat supply. Potentially, the struggle between competing framings and qualifications of how gas and district heating systems can play a role in future energy systems will determine the outcome. In this thesis, only shifts from individual to collective types of heating have been analysed, and not shifts from one type of collective heating to another, e.g., a shift from gas to district heating grids. This means that a shift from gas grids to district heating faces established infrastructure, which often delivers high-quality stable energy supply with established socio-technical assemblages of organisations, institutions, regulations and actors. Countries with a high share of individual heating will have to decide whether to continue with individual heat supply and shift to electric heat pumps or biomass boilers, or shift to district heating systems. This entails establishing central and coordinating organisations, new customer and consumer relations and massive investments in infrastructure among other factors.

8.2 TOWARDS AN UNDERSTANDING OF HEAT GOVERNANCE ASSEMBLAGES

I have used the term *assemblage* (Çalişkan and Callon 2010) to describe the heterogeneous elements that form part of enabling, governing and maintaining heat planning activities among stakeholders using tools, regulations, knowledge, training and expertise while bearing in mind existing infrastructure and future scenarios of potential energy system configurations. Such assemblages are loose connections of these diverse elements and are not necessarily stable networks producing predictable outcomes. The notion of assemblage highlights an important ontological argument, i.e., that all agency is local, and that the assemblage enables action to be taken. There is no shared system logic but instead sporadic attempts by diverse actors to develop the system in line with their own particular perspective. The energy planning literature also has a significant focus on the term *local*, but with a different interpretation. Often, *local* is defined as an area or elements in close contact. Prioritising geographical local elements tends to ignore some elements in the assemblage such as regulations, legislation, knowledge, decision-making tools, and the energy infrastructure that enables the transmission and use of “locally” produced energy. All of these elements become local when they are considered part of the assemblage, but they are sometimes excluded from the analysis when *local* is understood in spatial terms.

In this thesis, I have argued that it is important to consider the diverse elements that constitute the particular assemblages that facilitate or restrict heat planning. Stakeholders, planners and decision makers navigate uncertain situations using their tools, expertise and plans (Article 3) and by adhering to national regulations, societal drivers framing technologies and the specific financing and ownership situations available (Article 2). Article 3 showed that all of these heterogeneous elements enabled the planning and implementation of a specific “local” technology - the TES. Even infrastructural systems that are often considered *national* and take an aggregated view, such as the gas systems covered in Article 2, required local planning and stakeholders for their implementation. In the Netherlands, the UK, and Denmark, the municipalities, utilities and suppliers were of central importance in the transitions.

8.3 ELEMENTS OF CONVERGENT GOVERNANCE ASSEMBLAGES

The articles that constitute this thesis have identified a number of important elements in navigating uncertain transition processes and enabling governance assemblages to facilitate the planning and implementation of new technology. Article 2 identified the *drivers, technology qualities, ownership, financing, actors, coordination, policy and governance* as elements that contribute to the convergence of collective work. 7 discuss these elements in depth.

Establishing common drivers such as energy efficiency or decarbonisation targets was central since these framings of technological qualities encouraged actors to develop common orientations. Technological framings were central to establishing drivers and presenting technologies as societal problem solvers. Framing technologies in specific ways highlights some qualities while obscuring others. Such framings were not interpreted or understood in the same way by all the actors. However, they did produce a common direction with room for individual interpretations. Articles 2 and 3 present some examples such as framing gas supply as *smoke free* in the UK, reframing Dutch gas as a *scarce resource* instead of an *abundant resource,* or the deliberations about whether the thermal energy storage in Greater Copenhagen should be a *short-term* or *seasonal* storage. Within these framings, there was room for the scattered agents to navigate and align their own agendas in order to contribute to the collective work.

The specific ownership and financing models were mostly different configurations of public and private cooperation, especially with public financing for constructing the grid infrastructure. Several different models were identified such as direct public ownership in the UK, public-private partnerships in the Netherlands and municipal ownership with access to low interest loans in Denmark. They all included long-term perspectives and a guarantee that the infrastructure would remain useful in the future.

No actor, organisation or institution was solely responsible for the development of the infrastructure or technology in the case studies, but instead they relied on coordination between many stakeholders. Articles 2 and 3 demonstrate the importance of collaboration between municipalities, utilities and cooperatives to invest in and implement the technologies with the help and support of governments, plans, strategies, and regulations. The *local* actors and their expertise were central to the implementation of new technology, but so were the tools, regulatory conditions, access to technology and finance. In particular, the thesis finds that coordination between actors occurs through knowledge generation and the circulation of plans, strategies and other epistemic devices.

The specific regulatory tools, policies and governance devices contributed in a number of different ways. In several of the examples, governance devices were central to defining the qualities of the technology such as gas being a *smoke free* fuel. Governance devices, such as the Danish heat supply act, also mandated actors to analyse the potential of the technologies in question. Such *governing at a distance* brought the heat supply systems into being by raising awareness of their benefits. Most of the regulatory and governance devices identified and analysed in this study maintained the independence and autonomy of their users, while simultaneously shaping their conduct. The Danish heat supply act is an example of how the municipalities were tasked with analysing options for heat supply, albeit using specified methodologies and assumptions. The NECPs covered in Article 4 represent a similar case of *governing at a distance* in that they can potentially bring new technological options and pathways into being by mandating that the EU-27 countries analyse their particular situations and how to move forward.

These elements should not be seen as a comprehensive list, and a limitation of the findings is the limited empirical material on which they are based. As I argue below, further research should investigate the conditions surrounding planning in diverse settings in order to identify those that are important for successful heat planning and governance.

8.4 NAVIGATING HEAT PLANNING PROCESSES

Overall, the term *convergence* (Callon 1991) describes the necessity of coordination, alignment and a mutual direction for developing systems with collective agency. In convergent systems, actors, stakeholders and planners are aware of a common aim and direction, while each is able to carry out their specific tasks. Although different actors specialise in their tasks, they are still able to communicate about the common direction. Just as in the case of a ship, where the captain, mate and engineers have their individual tasks to fulfil, or a company where product development, marketing and sales departments all coordinate and share tasks, planners, investors, utilities, policy makers, and employees in energy agencies and ministries need to coordinate their scattered agency and work together toward common goals. Articles 2 and 3 describe similar situations in the cases of successful implementation of new infrastructure and technology. Article 2 finds that governance assemblages set out shared goals and drivers that guided the action of the various system actors. In Article 3, the long-term development of the Greater Copenhagen district heating system and the Danish heat supply legislation meant that the actors had been cooperating for a long time under similar conditions. When national low-carbon energy plans outlined the necessity to decarbonise the Greater Copenhagen district heating system, it gave the TSOs, CHP plans, waste incineration facilities and utility companies a common goal. Convergent networks can collectively organise the work of actors while remaining responsible for their own operations. In interconnected energy systems, such as the Smart Energy Systems approach, this coordination across energy supply vectors most likely becomes even more important.

Therefore, a central task for heat planning is to simultaneously identify overall shared problems and challenges for heat planners and other actors engaged in low-carbon energy development, while allowing and accommodating multiple understandings, approaches and agendas. A common ‘language’ in terms of shared calculative methods, system understandings and assumptions may prove important here, as it can improve coordination and communication between diverse agents. Examples include the EU mandating countries to produce NECPs or the rules for socio-economic calculations for district heating in Denmark. Knowledge production describing heat supply is crucial in developing these understandings: not by imposing a single shared understanding, but instead by producing a shared direction that actors with different roles and responsibilities can work towards. New tools, regulations and devices will need to contribute to this work: energy system flexibility, sector integration, energy efficiency from primary energy supply to households' end-consumption are all aspects that future energy system imaginaries highlight, but they will need to be made measurable, tangible and discrete before they can be governed.

8.5 LIMITATIONS

A major limitation of the findings and conclusions in this thesis is the ability to generalise across the EU countries. As with all case studies, it is not possible to simply extrapolate the results from one case and assume they apply to other. While some similarities where found in the historical analysis of Denmark, the UK and the Netherlands, the specific findings can only be interpreted in other countries with caution. Furthermore, since the case studies takes an historical approach, the governance, policies and drivers should not be assumed to be the same today as 40-50 years ago.

While Article 1 and 4 include all countries in EU (with UK included in Article 1), they do not provide a full picture, but only describe heat supply to the extend possible with existing data. They also aggregate heat supply to a national level, and does not consider the different configuration within countries. Thereby they do not examine differences in heat supply between urban and rural settings.

Each of the four articles have their own limitations, and these are discussed in the articles themselves.

These limitations must be considered when reading, interpreting and using the findings. On the other hand, the theoretical understanding, methods used, and overall approach to understanding heat supply could be applied, adopted and used in other settings. Hopefully the work can inform those who wish to study heat planning or are engaged in heat planning activities themselves, not by prescribing conclusions or findings but by shaping which elements might be important to consider. This also highlights the need for future work, something I address in the next section.

8.6 FUTURE RESEARCH

The findings presented in this thesis highlight new unexplored avenues of research in heat and energy planning. In the following, I outline several that I believe would contribute to the energy planning literature and improve understanding of how to promote change in supply infrastructure.

There is scope for further exploring the conditions that enable successful energy transitions. There is potentially much to learn from historical and current examples. In particular, consideration of how different actors coordinate their sporadic attempts to develop collective infrastructure may be of importance. Ethnographic research may be well suited for continuing to analyse how energy planners plan future energy supply. I have presented one case study here, but more are needed in order to identify trends that are more general. Such an approach focused on the national or international levels would also be valuable. Much research has focused on what is often labelled "the local level", e.g., the location where investments are made and infrastructure is implemented. However, those who produce the governance tools, policies, regulations and calculation models that, as I have argued in this thesis, enable "local" planners to act, are often ignored. I therefore believe that it would be fruitful to examine how energy planning is conducted in ministries, energy agencies, the EU commission, etc.

Article 3 and this conclusion discuss the importance of convergent networks; a crucial element of which is trust between actors. Therefore, future studies should attempt to follow the everyday work of actors and how they cooperate. While such a task will be methodologically difficult and would require significant effort, it could determine how to measure convergence and trust in heat planning networks.

Research into how actionable tools are developed is also needed as they enable energy planners to "see" their heat and energy systems in new ways that support a transition to low-carbon energy systems. A number of research projects are currently producing new computer tools for heat planning: Thermos, Hotmaps, Rewardheat and Heat Roadmap Europe, to name a few. Some of these are even developing their tools together with planners, city administrations and utilities. My understanding is that although these tools are expected to work by simply highlighting new options, e.g., a form of producing alternatives, much work will be needed to identify exactly which futures they enact and determine how they enable actors to act and how they influence actors in specific, partial knowledge positions with diverse responsibilities. These projects also need to not only develop tools, but also to follow their use to see how they equip actors for engaging with an uncertain reality.

For municipalities, utilities, energy agencies, ministries, national governments and the EU commission and parliament, there is plenty of work to do to produce governance tools that can translate decarbonisation goals into specific and measurable action. The many scattered agents working with energy system transitions need knowledge and governance devices that enable them to carry out their work and make it quantifiable with stable long-term financial and market conditions. As mentioned above, governance assemblages need to ensure convergence, trust and a similar direction for the many actors involved. At the same time, those making the tools need to reflect and continuously adjust to emergence of new challenges, overflows, and potential in the decision-making process.

Future heat and energy planning is not a linear process from innovation and knowledge to implementation. Instead, it is a complex process involving multiple actors with diverging agendas operating under high uncertainty. I believe a first step to advancing low-carbon heat supply as a part of decarbonised energy systems is to accept this messy reality and attempt to understand and deal with its complexity, instead of continuing to approach it as stylised stable interactions.

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APPENDIX A – ARTICLES

Article 1: N. Bertelsen, B.V. Mathiesen, EU-28 Residential Heat Supply and Consumption: Historical Development and Status, Energies. 13 (2020) 1894. https://doi.org/10.3390/en13081894.

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Article 2: N. Bertelsen, S. Paardekooper, B.V. Mathiesen, Implementing large-scale heating infrastructures: experiences from successful planning of district heating and natural gas grids in Denmark, the United Kingdom, and the Netherlands. Energy Efficiency 14 (2021). https://doi.org/https://doi.org/10.1007/s12053-021-09975-8.

First published in Energy Efficiency, volume 14, article number 14, 2021 by Springer Nature

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Article 3: N. Bertelsen, M. Caussarieu, U.R. Petersen, P. Karnøe, Energy plans in practice: The making of thermal energy storage in urban Denmark, Energy Res. Soc. Sci. 79 (2021) 102178. https://doi.org/10.1016/j.erss.2021.102178.

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Article 4: N. Bertelsen, B.V. Mathiesen, Gaps and ambitions in the goals and policies of the EU-27 National Energy and Climate Plans

Submitted to Energy Policy

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EU-28 Residential Heat Supply and Consumption: Historical Development and Status

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Received: 19 March 2020; Accepted: 9 April 2020; Published: 13 April 2020

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Abstract: EU is moving towards a climate neutrality goal in 2050 with heating of buildings posing a major challenge. This paper provides a deep understanding of the historical development, path dependency and current status of the EU-28 residential heat sectors to inform strategy and policy makers and to open up this black box. Data is combined for buildings, installed technologies, fuel consumption and energy supply for Member States from 1990 to 2015, to analyse the importance of large-scale infrastructures and supply chains. Primary energy supply for residential heating is mainly based on fossil fuels; 70% in 2015 with 69% imported. The building level technologies are dominated by non-condensing boilers and stoves. Primary and final energy consumption decreased in spite of an increase in the total occupied living area in most countries. Path-dependency effects are found in the residential heat supply in EU. The analysis show path-dependent trajectories are present in most Member States, especially regarding natural gas infrastructure. The period shows many options for decarbonisation are not used to the full potential, e.g., energy efficiency in buildings, district heating, heat pumps. Past experiences should be considered when developing new decarbonisation strategies in Member States and on the EU level.

Keywords: residential heat supply; heat; decarbonisation; EU-28; supply chain; energy efficiency; data quality; path dependency

1. Introduction

To fulfil the targets set in the Paris Agreement [1], The European Union (EU) have set ambitious targets for the energy transition towards 2030 [2] and 2050 [3], focusing on increasing renewable energy (RE) penetration, energy efficiency (EE) and lowering greenhouse gas emissions. Heating and cooling for residential, service and industry accounts for ~50% of the EU's primary energy supply (PES) [4,5].

Due to its physical properties, heating cannot be distributed, sold or exchanged over long distances, contrary to the international electricity and gas systems that characterize contemporary EU energy supply. This results in a local and contextualized situation for the EU-28 heat markets, still with significant unknowns. Compared to the electricity and the gas sectors, heating remains largely a black box with large unknowns to researchers and policy makers.

In order to address these knowledge gaps, heat transitions have received considerable attention both from the European Commission [6] and several Horizon 2020 research projects [7–10], presenting possible pathways towards RE based heat supply. Recent studies [11–13] contributed with open-source datasets of the EU-28 heating and cooling sectors for 2015, which also proved important in the realization of this study. A body of literature address policies for promoting renewable heating [14–16], for residential EE [17–19] as well as assessing the balance between heat supply and heat savings [20,21]. Future renewable and energy efficient heating and energy supply can be composed of multiple technologies such as waste heat, combined heat and power (CHP), heat pumps, geothermal, which can be utilized through district heating (DH) networks combined with the use of individual heat pumps in areas with low heat consumption densities in addition to significant heat savings in all buildings [22–24].

While these perspectives are valuable, they lack a consideration of the historical development of heating infrastructures, end-use technologies and the infrastructural systems that distribute the energy supply. Residential heating today is either supplied from collective infrastructures such as gas or DH grids, or in the form of solid or liquid fuels that are easy to transport without dedicated infrastructures, to be consumed in individual boilers and stoves. Not only are the household installations important, but the supply chain networks that the heat delivery depends on are as well. Technological change can be inhibited by existing infrastructures due to path dependency effects, such as economies of scale, network effects or knowledge and preferences of users and decisions makers [25]. Technological systems can be subject to increasing returns of scale and sunk costs contributing to a lock-in effect into incumbent technological choices [26]. The aim of this paper is to expand the knowledge about the current state of residential heating and the development trajectory in the EU-28 to facilitate and inform further transitions.

Historical accounts of the development of heat supply have been presented for DH supply in the EU and worldwide [27] and country specific approaches include Austria [28] and a more general energy system approach for Denmark [29] as well as technology and country specific accounts such as the Polish heat pump market [30]. Taking a historical perspective of the development of residential heating in Sweden and The UK, Gross and Hanna conclude that:

> *"To overcome lock-in to carbon-intensive heating, policymakers seeking to achieve carbon targets should draw on a historical perspective of how to support path-dependent change in heat transitions"* [31]

This paper adds to this understanding by describing the historical technological development of the EU-28 residential heating sectors, describing development trajectories, the current state-of-the-art and highlighting instances of path-dependency and transitions. We present an assessment of the current status and development of the EU-28 residential heat sectors from 1990 to 2015, to add to the knowledge of the development of EU residential heating. To our knowledge, no such studies have been carried out before, and we therefore add to the energy system transition debate by combining historical path-dependent perspectives with a discussion of future potential developments. This study establishes a broad understanding of residential heat supply by analysing PES, distribution infrastructures, end-use technologies, energy import shares and final energy consumption (FEC) as well as the heat consumption intensity per occupied living area in EU member states (MS). This allows to analyse the development of the residential heat sector as well as to provide an important input to understanding the departing point of the renewable heating transition in the current situation. Based on this analysis we provide general heat planning and development guidelines for countries largely supplied by individual heating, with extensive coverage of gas heating and for countries with high shares of district heating supply. The paper show that decarbonisation and renewable heating strategies should consider technological contexts and historical path-dependency from which future solutions will depart and likely struggle with. This should be considered by researchers, policy makers and decision takers on local, national and international policy scales, dealing with the decarbonisation of energy systems.

2. The Residential Heat Supply Chain

To assess the status of the EU-28 heating sectors, it is important to differentiate between different types of heating infrastructures. While biomass boilers, gas boilers and DH substations in themselves are different technologies, they also rely on vastly different supply chains. The technological network effect are important sources of path-dependency, as the supply chain elements must be compatible with the overall system [25,32]. While biomass boilers utilize fuel from different sites such as forests or wood processing industries, DH or gas relies on specific infrastructures to deliver the energy to the building [33]. Individual boilers are fuel specific and cannot easily be repurposed to use other fuels. Natural gas networks can be adjusted to integrate moderate amounts of biogas or hydrogen gasses into natural gas supply. For example, IRENA estimate that, depending upon the state of the gas grids, up to 10–20% hydrogen can be mixed with natural gas supply [34], but with potential impacts on end-use devices. DH grids are fuel agnostic, and the distribution grids can be used with several different supply types [33]. Switching to a renewable DH supply can depend on a decrease in distribution temperatures, affecting DH networks and building level installations [35]. All residential heat supply technologies are as such affected by certain types of technological lock-in due to the supply chains of installed technologies and infrastructures.

Building upon this understanding of path-dependency from technological supply chains [25,36] and drawing upon energy system literature describing a holistic approach to assessing energy systems from production to demand [37], this paper propose that the residential heat supply chain can be understood through five distinct focal points that informed the research design of this paper:

1. Primary energy supply and CO_2 emissions
2. Heat distribution infrastructures
3. Final energy consumption for residential heating and end-use heating technologies
4. Heat consumption intensity per living area
5. Useful energy demand

2.1. Primary Energy Supply and CO_2 Emissions

PES is a measure for the energy sources used to deliver heating, including conversion, transmission and distribution losses. PES estimate the total energy supply that enters the energy supply chain, and this measure allows a comparison of the energy amounts consumed by different heating technologies. For example, CHP plants utilize otherwise wasted heat from electricity production and distribute this to heat consumers. In order to compare this to heat production from a gas boiler located in the household, PES is a useful measure.

PES also focus on the primary fuels and not energy carriers or energy delivery. This means in practice that PES account for the fuels used to produce energy carriers such as DH or electricity. CO_2 emissions can be assessed based on PES as this accounts for the full energy amount used and thus the total CO_2 emissions released because of the heat consumption.

2.2. Heat Distribution Infrastructures

The different types of distribution infrastructures can be assessed with the concept of tightly or loosely coupled systems [38]. Here, a simple distinction between large-scale collective or individual heat supply is made. Materially tightly coupled heating infrastructures have specific infrastructures for energy delivery to the household and thus constitute large-scale collective supply infrastructures. Electricity, gas and DH grids fall in this category. Loosely coupled systems depend upon other infrastructures to deliver their services and characterize the individual heat supply technologies. Residential heating using oil, biomass or coal boilers relies on diverse distribution networks to deliver the energy carrier at the households for energy consumption. The different types of heating and their categories are presented in Table 1 below.

Table 1. Heat distribution infrastructure categories.

Heat Supply Type	Type of Infrastructure
District heating Gas Electricity	Large-scale collective infrastructure
Oil Biomass Coal	Individual heat supply

2.3. Final Energy Consumption for Residential Heating and End-Use Heating Technologies

FEC is the amount of energy delivered at the place of consumption, to be used in end-use technologies. End-use heat production technologies are the technologies used to produce heat energy, either directly from fuels such as household boilers using gas, oil, coal or biomass, or from electricity using electric radiators or heat pumps. While most heat production technologies are located at the place of consumption, DH is different. With DH supply the heat production happens before the distribution step, and not after [33].

2.4. Heat Consumption Intensity per Living Area

Heat consumption intensity is a measure for the amount of residential heat consumption per residential area heated. It describes the relative energy consumption compared to the living area that is being used, and is a measure for the average heat consumption per living area in a country. Several accounting measures for residential living area exists, which will be outlined in the materials and methods section below.

2.5. Useful Energy Demand

The useful energy demand is the need for residential heat that is met by the infrastructural supply chain system. This is difficult to assess as it is usually not measured and depends upon building stock quality, efficiency of building end-use technologies, heat distribution systems within the building, energy billing, heat control systems and heat consumption practices by the consumers and more. Van den Brom et al. estimate around 50% of the heat demand to depend upon the residents and their practices and 50% to depend upon building characteristics [39].

3. Methods and Empirical Data

Departing from the supply chain perspective presented above, this paper investigates the EU-28 residential heat sectors as systems that are connected from the production to consumption of energy. This was studied by investigating quantitative data sources available for residential heating across the EU-28 to compare longitudinal and cross-national developments. This approach allowed investigating the development of the current heat supply of the MSs and how they compare. By choosing a research design based upon existing databases, this paper investigates the extent of current available knowledge of the EU-28 residential heat consumption and the state-of-the-art of the sector. Most empirical data on residential heat consumption measures FEC, the energy amount consumed. The research design departs from this statistic as it is widely available and often reported by national statistical agencies. Based on this, PES, distribution infrastructures and FEC per residential living area can be derived with additional datasets. This research design has two main purposes. First, to bring residential heating forward by providing new knowledge of the development and current status. Second, to highlight knowledge gaps that black-boxes residential heat consumption, thus making it difficult for analysts and policy makers to address.

3.1. Primary Data Sources

The most comprehensive source of historical residential heat consumption data for the EU-28 found is the Odyssee-Mure (OM) database [40], an EE database collected in the OM research project with 30 partners and coordinated by the French Environment and Energy Management Agency (ADEME), with the database being managed by Enerdata. The OM database includes yearly residential heat consumption data including fuel supply collected from national energy agencies.

The climate corrected FEC for EU-28 residential heat consumption from OM is 2625 TWh in 2015 and deviates 8% from Pezzuto et al. [12] and Heat Roadmap Europe 4 [41] result which both are around ~2850 TWh. It is difficult to validate this data quality, but in their study of the 2015 space heating (SH) and domestic hot water (DHW) market in Europe, Pezzuto et al. [11] categorize their results as within 6% of PES to be *close* and find differences as large as 47% for PES compared to other studies. The primary quantitative data sources used in this study are presented in Table 2 below.

Table 2. Primary data sources.

Content of Dataset	Reference	Data Discrepancies in Datasets	Timeframe Covered
Residential heating technologies	[11]		2015
Final Energy Consumption for heating	[40]	Missing data	1990–2015
Occupied living area	[40] [42]	Missing data Discrepancy between quantifications	1990–2015
Heating degree-days	[43]	Missing data	1990–2015
District heating and electricity fuel supply	[44]	Missing data	1990–2015
Electricity and district heating production units (CHP, power plants or heat-only)	[45]		1990–2015
Energy conversion losses and district heating distribution losses	[46,47]	14 countries included in the dataset (90% of EU-28 heat demand)	Constant
CO_2 emission factors	[48]		Constant
Energy dependency	[49]	Only covers fossil fuels e.g., not imported biomass	1990–2015

3.2. Data Handling and Flow

The analysis is based on a combination of the data sources presented in Table 1 above. Figure 1 below illustrate their connection for creating the analyses presented in the paper. Final energy for heat consumption [32] is first climate adjusted [33] using heating degree days (HDD) [43] to estimate consumption in a standard year. The FEC is adjusted using the average HDD per country between 2000 and 2015.

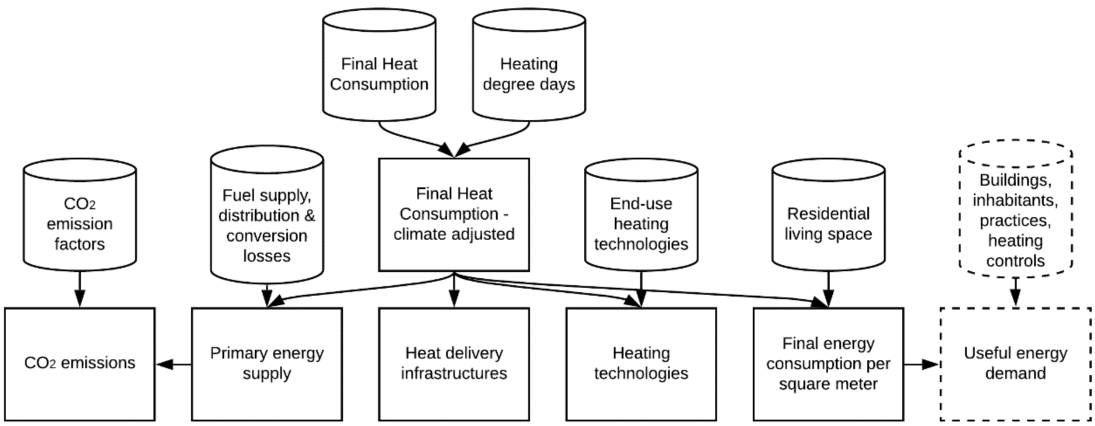


Figure 1. Representation of the data structure and relation between datasets used for the analysis in this paper. Useful energy demand is in a dashed box as this could not be estimated for this paper due to missing data.

To calculate PES, the primary fuels used in DH and electricity production must be estimated. This is done using Equation (1). *FEC* denote the measured final energy consumption. Distribution efficiency is denoted with η_{dist} and is calculated as 1–distribution losses. Production efficiency is accounted for using η_{prod}, and is calculated as 1–production losses. The primary fuels are estimated by finding the fuel supply share for each primary fuel, denoted α_{fn} for each primary fuel.

$$PES = FEC \cdot \left(\frac{1}{\eta_{dist}} \right) \cdot \left(\frac{1}{\eta_{prod}} \right) \cdot \begin{pmatrix} \alpha_{f1} \\ \alpha_{f2} \\ \cdots \\ \alpha_{fn} \end{pmatrix} \tag{1}$$

Energy losses from CHP plants can be attributed using different methods. This paper uses the energy content method, where losses are distributed based on the fractions of electrical and thermal output from CHP plants [50]. The principle for the share of losses attributed to the heat production from CHP plants is as follows:

$$l_Q = \frac{Q}{(E+Q)} \tag{2}$$

$$l_E = \frac{E}{(E+Q)} \tag{3}$$

where l_Q and l_E denote, respectively, the fraction of energy losses allocated to the heat production and electricity production, and Q and E, denote, respectively, the net heat and electricity production share.

Based on the PES, total CO_2 emissions and average CO_2 emission intensities expressed as gCO_2/kWh can be derived using emission factors of CO_2 per energy content [48]. Nuclear electricity is assumed produced with an efficiency of 33% according to IEA standards [47]. Losses from natural gas transmission and distribution are estimated by the Danish Energy Agency to be around 0.005% - 0.03% for natural gas distribution networks on a European scale [51]. These losses are practically insignificant and not included in this paper.

CO_2 emissions from combustion of biomass are uncertain and difficult to ascertain [52]. IPCC guidelines attributes CO_2 emissions from combustion of biomass to the land use, land-use change and forestry (LULUCF) sector [48], and as such they are typically not included in estimations of energy sector CO_2 emissions to avoid double counting in national and international statistics. It is although uncertain when and to what extent CO_2 emissions are reabsorbed in the LULUCF sector [53]. To assess the development of biomass consumption for residential heating, this paper quantifies the direct CO_2 emissions in relation to residential heating, as it is uncertain to which degree these emissions are offset in the LULUCF sector.

Heat delivery infrastructures are categorized based on the supply chain perspective presented above. This paper differentiates between heat supply based on large-scale infrastructures or individual heating. The categorization of heat delivery infrastructures are as presented in Table 1 above. For each MS the share of individual and large-scale collective heating was investigated from FEC for heating. This gives an indication of which countries have managed to supply heating through collective infrastructures and which countries primarily have relied on individual heating units.

For the end-use residential heating technologies, only data for 2015 is available and therefore a historical analysis cannot be made. Nevertheless, it allows for a detailed account of the current technological situation in the EU-28 households, and of the FEC for heating by each technology.

To assess the residential heat consumption intensity, a measure of the residential living area is needed. Detailed historical statistics for the residential occupied or heated living area in the EU-28 is not available in detail. The European Building Stock Database (EUBD) provides one resource for total useful residential living area, but does not provide information about occupied area [42]. It is difficult to estimate how much of the useful living area is occupied, actually used or heated. The OM database contains the number of total and occupied residential dwellings and average number of square meters per country and year. This provides an assessment of the occupied living area per MS. Other sources include Pezzuto et al. [12] for a detailed account of building age for 2016 and the Entranze research project which provides building stock statistics for 2008 [54]. Different methodologies for data collection and assessment makes these databases difficult to compare while maintaining data quality, and this paper therefore uses the OM database due to maintaining data consistency.

From FEC and the occupied living area, the average residential heat consumption intensity measured in kWh/m^2 can be derived. As this is MS averages, there will certainly be residences in the MSs with higher or lower heat consumption intensities. Ideally, the assessment of residential heat consumption intensity would include an assessment of building stock quality, end-use technology efficiency and renovations made. Reliable historical data of the EU-28 has not been available for this study, and is therefore not included here. This is discussed further in Section 5 below.

3.3. Data Error Handling

Most of the datasets used for this paper had missing data or included data points, which were irregular. Residential heat consumption data was lacking for Romania (2012–2015), Greece (2015), and Belgium (2014–2015), which was estimated until 2015 by using the last year of available data.

Missing data in the residential occupied living area was estimated using linear interpolation, as the living area is assumed to have had a steady development from 1990 to 2015.

For The UK and Poland, total and occupied living area was reported as the same value in the OM database. As a 100% occupancy rate is regarded as unfeasible and likely a data error, the occupied living area was adjusted with an average European occupancy rate calculated as the yearly ratio between European occupied living area and European total living area. This ratio was found to be between 85% and 87% from 1990 and 2015.

The HDD data for Sweden had a significant drop for 1994, which was due to missing data for some regions on a NUTS2 level [55]. The Swedish 1994 HDD were estimated using the average Swedish HDD adjusted with a 1994 factor from the remaining regions.

Both Denmark and Latvia missed data about energy consumption for DHW. For Denmark, no energy consumption for DHW was reported. This was estimated using a DHW share of FEC for residential heating of 15.95% from [12]. Latvia missed data about energy consumption for DHW before 2001. This was estimated using an average DHW share of FEC for residential heating of 19.2% for Latvia from the period 2001–2015. Finally, the average dwelling size in Belgium was lacking from the OM database, which was estimated using data from Pezzutto et al. [12].

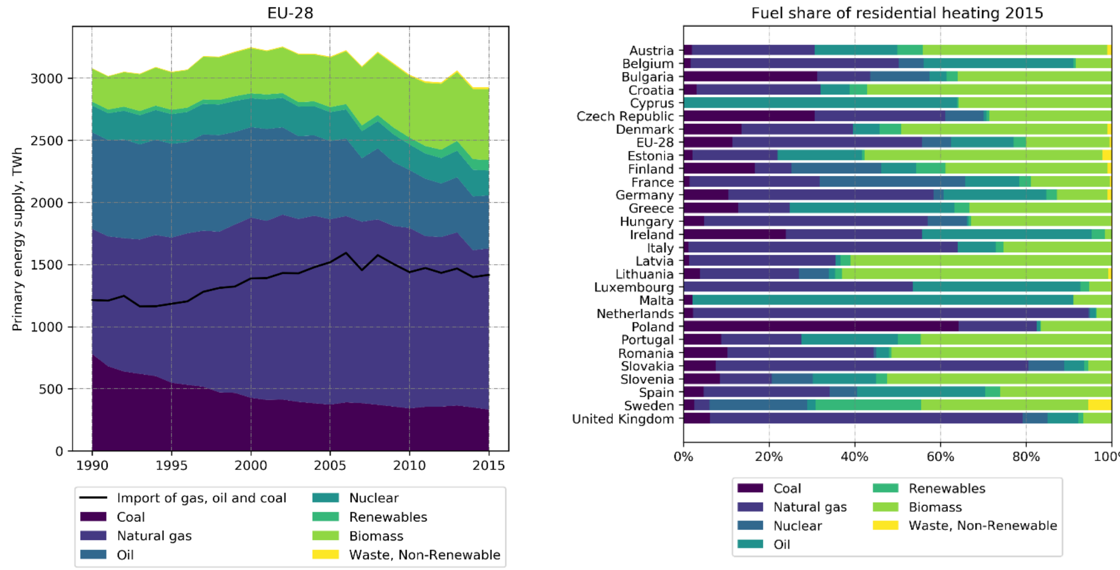
3.4. Software

All data processing and calculation was handled using the Python programming language [56] in Jupyter Notebooks [57]. Visualizations were made using the Matplotlib library [58].

4. Results

4.1. Primary Energy Supply for Residential Heating Consumption in the EU-28

The climate adjusted EU-28 PES for residential heating has remained around 3000 TWh/year from 1990 to 2015, as shown on Figure 2a. PES increased from 1990 levels at 3080 TWh to its highest in 2002 at 3255 TWh, before decreasing to 2927 TWh in 2015. The 25-year period remained within +5% and −6% of the mean PES consumption for the period of 3108 TWh, with the lowest consumption years in the period after 2010.



(**a**) (**b**)

Figure 2. (**a**) Development of primary energy supply for residential heating consumption from 1990 to 2015 in the EU-28 with the respective imports into the EU-28 of gas, oil and coal for residential heating. Results are climate adjusted. (**b**) Primary energy fuel share for residential heating in 2015 of the EU-28 member states.

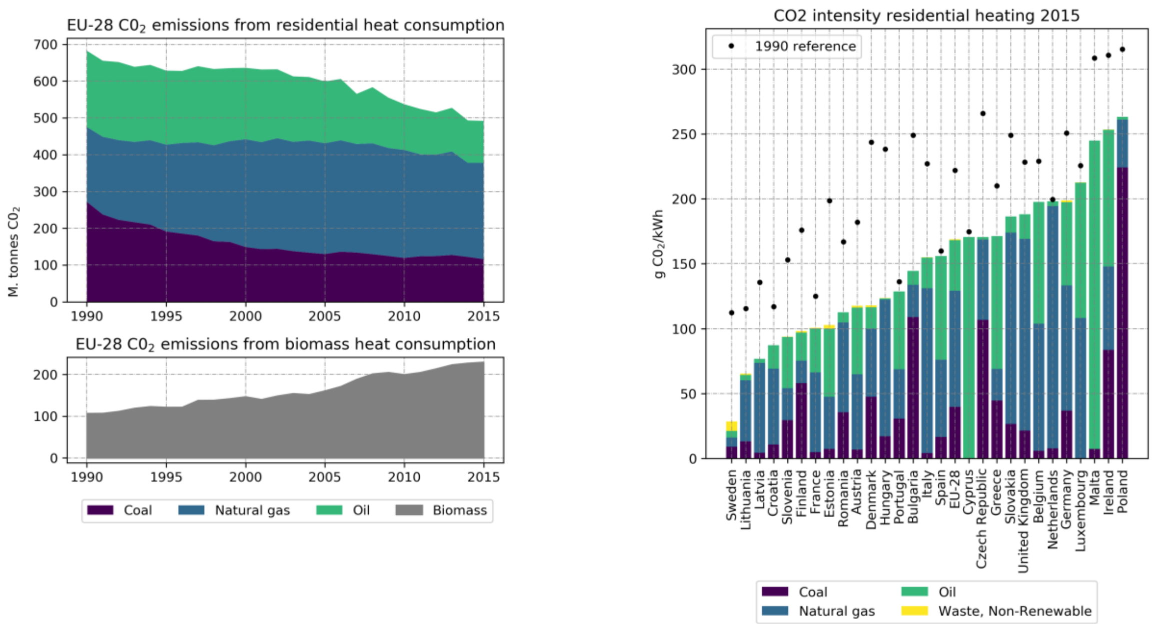
Natural gas is the single most used primary fuel for heating in the EU-28 increased from 1990 to 2015 to 1297 TWh accounting for 44% of the PES for residential heating. Natural gas PES increased from 1007 TWh in 1990 to its highest level in 2004 of 1510 TWh. 14% of the natural gas consumption was used in DH supply with the remaining 86% used in individual boilers. Coal PES more than halved during the period from 780 TWh in 1990 to 333 TWh in 2015, with two-thirds used in DH systems and one-third used directly for heating in boilers. The three countries with the highest coal consumption for residential heating in 2015 was Poland with 135 TWh, Germany with 62 TWh and the UK with 23 TWh, accounting for, respectively 41%, 19% and 7%, totalling 2/3 of the coal PES for residential heating in the EU-28. Nuclear PES for residential heating through electric heating or using heat pumps accounted for 216 TWh in 1990, peaking in 1999 at 249 TWh following a decrease to 200 TWh in 2015. In 2015, France alone accounted for 159 TWh of the nuclear PES used for residential heating, amounting to 79% of the EU-28 nuclear PES for residential heating. Oil PES decreased from 777 TWh in 1990 to 427 TWh in 2015, with Germany using 140 TWh of oil for residential heating in 2015. 95% of oil for residential heating was used in individual heating. Renewables, without biomass, are the single smallest supply source for residential heating in the EU-28, increased the PES with a factor 2.75 from 30 TWh in 1990 to 85 TWh in 2015. Sweden accounted in 2015 for 23% of the renewables in the EU-28 PES, with Germany and France following at 17% and 15% respectively. All renewables are used in either DH systems or with electric heating. Biomass saw a doubling in PES, going from 265 TWh in 1990 to 570 TWh in 2015 with 95% used in individual stoves. The top consumers in 2015 were France, Italy and Germany accounting for 15%, 14%, and 12% of the total EU-28 biomass PES respectively. Natural gas, biomass and renewable PES all increased during the period from 1990 to 2015, while coal, oil and nuclear PES decreased.

EU-28 energy imports of natural gas, oil and coal for residential heating increased from 1215 TWh in 1990 to 1417 TWh in 2015, an increase of 14%. The imports peaked in 2008 with 1576 TWh and decreased since then. In 2015, 69% of the fossil fuels for residential heating was imported from outside EU, more specifically 69% of natural gas, 42% of coal and 89% of oil was imported.

Figure 2b show the fuel share of PES for residential heating in 2015 for the EU-28 MSs. It shows a diverse fuel mix across the MSs, meaning that the PES for residential heating is difficult to compare between countries. A few countries have very uniform PES heat supply, such as The Netherlands, Slovakia and The UK where natural gas accounts for 92%, 74% and 73% of the PES for residential heating respectively. Cyprus used 64% oil and 36% biomass while residential heat on Malta was 89% based on oil. 64% of the PES for residential heating in Poland was in 2015 based on coal. Contrary to the countries with a high use of a single fuel are the countries that are using several different fuels. Only four countries have three fuels that each supply more than 20%, which are The Czech Republic (29% biomass, 30% coal and 31% natural gas), Ireland (24% coal, 32% natural gas and 40% oil), Spain (26% biomass, 29% natural gas and 30% oil) and Sweden (39% biomass, 24% nuclear and 25% renewables). While natural gas is the single most used fuel in the EU-28 for residential heating in terms of total PES, biomass is most used in terms of highest share per country. In 12 MSs (Austria, Bulgaria, Croatia, Denmark, Estonia, Finland, Latvia, Lithuania, Portugal, Romania, Slovenia, Sweden) biomass is the most used fuel, before natural gas with 9 MSs (Belgium, Czech Republic, Germany, Hungary, Italy, Luxembourg, Netherlands, Slovakia, United Kingdom).

4.2. CO_2 Emissions from Residential Heating in the EU-28

EU-28 CO_2 emissions from residential heating decreased from 1990 to 2015, primarily as a result of a shift away from coal and oil towards natural gas and biomass, as presented in Figure 3a below. The results of this analysis show a decrease from 683 M. Tonnes CO_2 emissions in 1990 to 494 M. Tonnes CO_2 emissions in 2015, a decrease of 28%. Natural gas accounts for the majority of the CO_2 emissions from residential heating at 53% in 2015, with oil and coal at 23% each.



(**a**) (**b**)

Figure 3. (**a**) Historical development of CO_2 emission from residential heating PES from 1990 to 2015 for the EU-28 MSs. CO_2 emissions from non-renewable waste incineration are not included in the figure as they only account for ~3 ‰ of EU-28 CO_2 emissions. Biomass includes only direct emissions and not for example uptake in the LULUCF sector or from direct and indirect land-use change. (**b**) Average g CO_2 per kWh heat used per MS in 2015 with 1990 as a reference level. Results are ranked from lowest average CO_2 intensity to highest in 2015.

The direct CO_2 emissions from biomass consumption are estimated to have more than doubled, from 107 M. Tonnes CO_2 in 1990 to 230 M. Tonnes CO_2 in 2015. If including all CO_2 emissions from biomass consumption, they would negate a large amount of the CO_2 emission reduction achieved in the EU-28 residential sectors from heating. As direct biomass emissions is the second largest source of

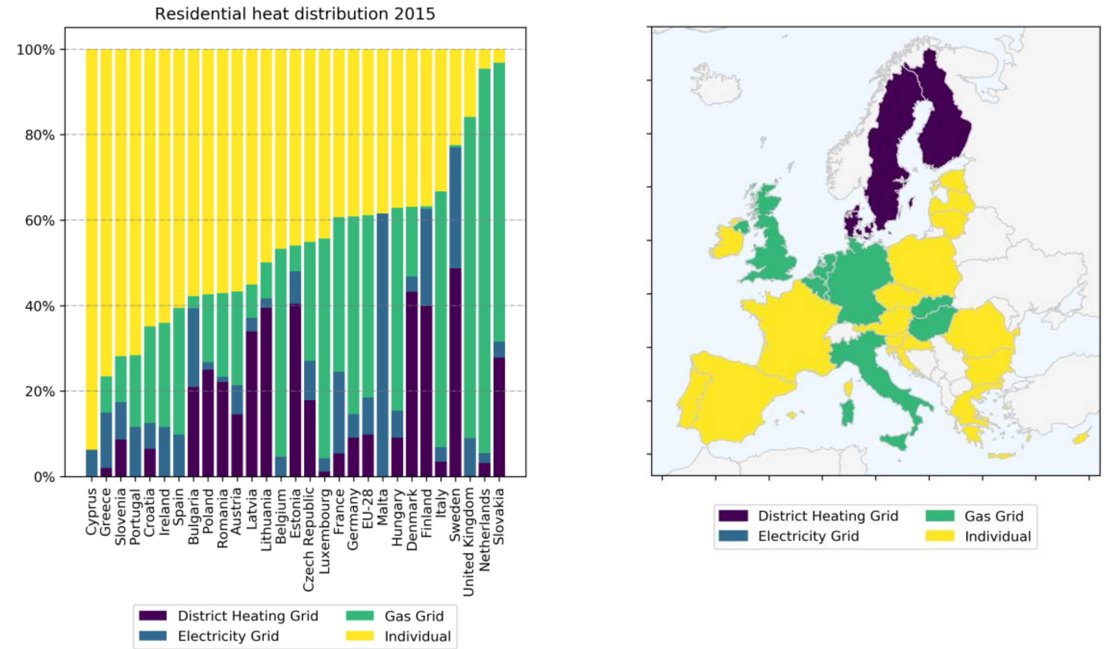
CO_2 emissions from residential heat consumption, it is important to consider the sustainability of this consumption and to which degree sustainable biomass is used for heating purposes.

Figure 3b shows that most MSs have seen a reduction in the average CO_2 intensity per kWh consumed for heating. In average, the CO_2 intensity decreased with 55 gCO_2/kWh among the EU-28 MSs from 1990 to 2015.

The results show Sweden to have the lowest average CO_2 intensity at 29 gCO_2/kWh due to a high concentration of biomass, nuclear and renewables in their heating sector. This was reduced from 112 gCO_2/kWh in 1990 due to a decrease in oil and coal consumption. Poland and Ireland have the highest CO_2 intensity among the EU-28 MSs due to the high consumption of coal and oil for heating. Poland and Ireland had a CO_2 intensity of 263 gCO_2/kWh and 253 gCO_2/kWh respectively in 2015. Denmark has achieved the highest reduction measured in gCO_2/kWh, from 244 gCO_2/kWh in 1990 to 118 gCO_2/kWh in 2015 also by reducing oil and coal consumption and switching to a high degree of biomass consumption. Portugal, Spain, Cyprus and The Netherlands have achieved very little or no reductions in the CO_2 emissions intensity from residential heating.

4.3. Residential Heat Delivery Infrastructures

Figure 4a illustrates the share of residential heating that is consumed via individual types of residential heating or from one of the large-scale collective infrastructures: DH, gas grids or electricity grids. It shows the range of diversity there is from countries with mostly individual based residential heating to countries that are primarily based on collective infrastructures. While 94% of the FEC is supplied by individual heating units in Cyprus, only 3% of the FEC is supplied by individual heating in Slovakia.



(**a**) (**b**)

Figure 4. (**a**) Share of residential heat consumption from individual heating or delivered via district heat networks, gas grids or electricity grids per MS. (**b**) Geographical representation of the most used heat delivery infrastructure or individual heating per MS.

Figure 4b shows the most used heat delivery method per country. 3 countries, Denmark, Finland and Sweden has expanded DH to be the single most used type of residential heating. 8 countries have deployed gas networks to the extent that gas delivers the highest amount of final energy for residential heating.

These are Belgium, Germany, Hungary, Italy, Luxembourg, Netherlands, Slovakia and The United Kingdom. In The Czech Republic, natural gas is the most used primary energy source, but individual heating is the most used residential heating type. This is due to primary natural gas consumption being split between direct use in gas grids and in district heating production.

Individual heating is the most used type of residential heating in 16 MSs in the EU-28. Malta is the only MS where electricity is the most used type of heating.

This illustrates which MSs have done active heat planning to expand supply infrastructures and in which MSs where residential heating primarily has been an individual concern. In the primarily individually heated countries, there seems to have been little coordinated effort to expand collective infrastructures in the residential heating sector. The MSs with high amounts of collective infrastructures seems to have actively promoted certain types of large-scale infrastructures.

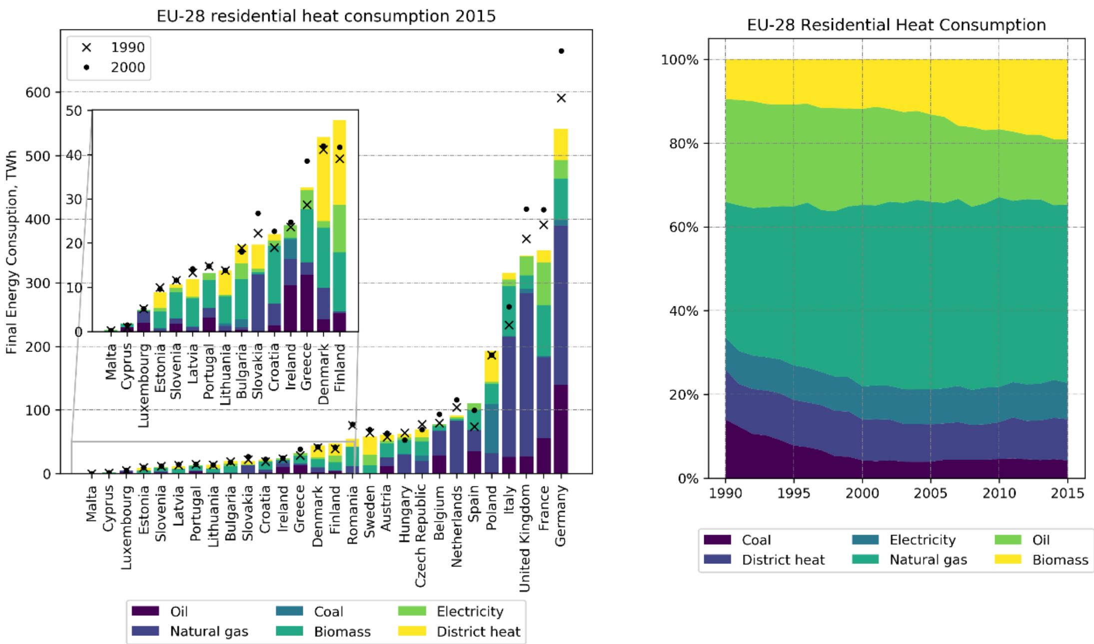
The MSs with high DH shares, Finland and Denmark have relatively low estimated average CO_2 emissions from residential heating, with Sweden having the lowest average CO_2 emission from residential heating of the analysis. Denmark, Finland and Sweden were all able to make significant decreases in the CO_2 emission from residential heat consumption from 1990 to 2015, showcasing the ability of shifting fuel supply in DH systems.

But collective heating infrastructures are not synonymous with low-carbon intensity for residential heating. Of the MSs primarily using natural gas for heating, 6 out of 8 (The Netherlands, The UK, Slovakia, Luxembourg, Belgium and Germany) have higher average CO_2 emissions from residential heating than the EU-28 average. Lithuania, Latvia, Croatia and Slovenia all have low average CO_2 emissions from residential heating due to high amounts of biomass in their heat supply. France is also below 100 gCO_2/kWh due to biomass and the high amount of nuclear power in the French electricity supply.

4.4. Residential Final Heat Consumption and End-Use Technologies in the EU-28

Among the EU-28 MSs a large diversity in heat delivery methods and the scale of consumption can be observed. Figure 5a show the residential heat consumption for each MS in 2015 and the contribution from each end-use technology. The FEC for residential heating in the EU-28 was 2625 TWh in 2015. Germany is the highest consumer of final energy for residential heating in the EU-28 at 543 TWh in 2015, followed by France, UK and Italy who consumed 351 TWh, 342 TWh and 316 TWh in 2015 respectively. Germany, France, UK and Italy together consumed 60% of the FEC for residential heat consumption in the EU-28 in 2015. Residential heat consumption increased from 1990 to 2000 in Germany, France, Netherlands and UK, but decreased from 2000 until 2015.

Italy and Spain have increased the residential heat consumption from 1990 until 2015. Figure 5b illustrate the development of the share for each heat delivery technology of the total residential FEC in the EU-28. In 1990, natural gas accounted of 33% of FEC for residential heat in the EU-28, which expanded to 43% in 2015. Both oil and coal FEC decreased from 25% and 14% to 16% and 4% respectively during the period from 1990 to 2015. Biomass, as the only individual type of residential heating increased from 10% to 19%. DH decreased slightly during the period from 12% to 10% and electric heating increased slightly from 8% to 9% of FEC. On an EU-28 level, Figure 5b illustrate that the residential heat supply display path-dependent characteristics. No large shifts or changes in FEC for residential heating has been observed from 1990–2015, while gradual fuel changes away from oil and coal are evident.



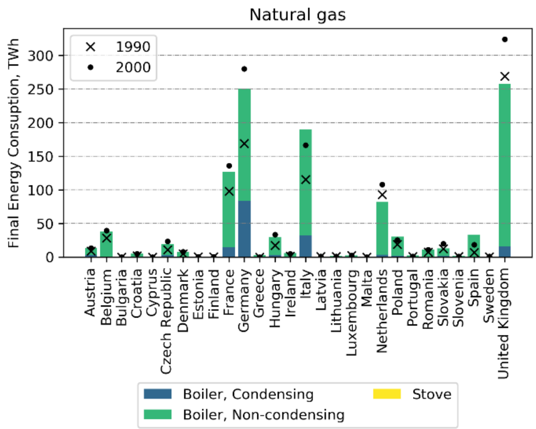
(**a**) (**b**)

Figure 5. (**a**) Final energy consumption for residential heat consumption in the EU-28 in 2015. MSs with residential heat consumption lower than 50 TWh are enlarged in the inset. The residential heat consumption from 1990 and 2000 is included to show the development of final energy consumption for residential heating. (**b**) Development of final energy consumption share for residential heating in the EU-28 from 1990–2015.

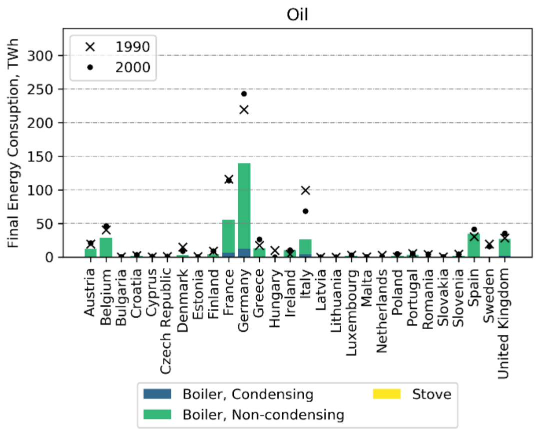
The FEC of end-use technologies that delivered the residential heat consumption in 2015 are presented in Figure 6 below. It shows overall that the end-use residential heating technologies in the EU-28 MSs are not state-of-the-art technologies. The majority of end-use natural gas and oil equipment are non-condensing boilers and most individual heat consumption from biomass is from stoves. According to the data, residential heat consumption from coal is only from non-condensing boilers. Electric heating is primarily supplied by electric radiators, with Sweden being the MS with most individual heat pumps, supplying around 39% of the Swedish residential heat consumption met by electricity. The largest consumer of electricity for residential heating, France, only supply about 1% of the residential heat consumption with heat pumps. The majority of DH is produced in CHP plants.

Overall, and with a few exceptions, the FEC for residential heating displayed path-dependent traits. Many MSs FEC per fuel in 2015 was close to the 1990 and 2000 levels, and as such does not display large shifts in residential heating consumption.

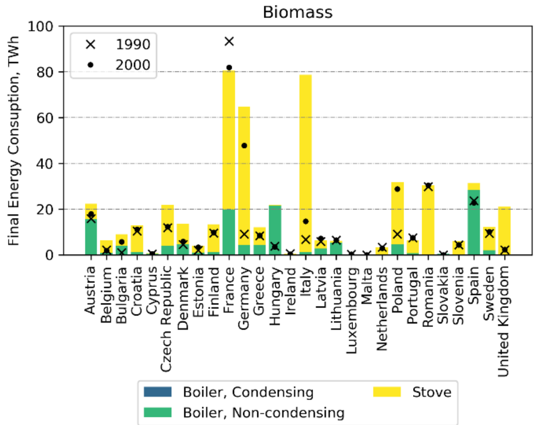
In absolute terms, the majority of natural gas FEC for residential heating was consumed in five countries: The UK (269 TWh), Germany (169 TWh), Italy (115 TWh), France (98 TWh) and The Netherlands (93 TWh) making up 84% of the EU-28 FEC of natural gas for heating in 2015. While Natural gas FEC decreased in The UK and The Netherlands from 1990 to 2015, in France and Germany it increased from 1990 to 2000 but then decreased again to 2015. In Italy, the natural gas consumption increased from 1990 to 2015. Germany and France were the two top consumers of oil for residential heating, with a consumption of 220 TWh and 116 TWh respectively in 2015.



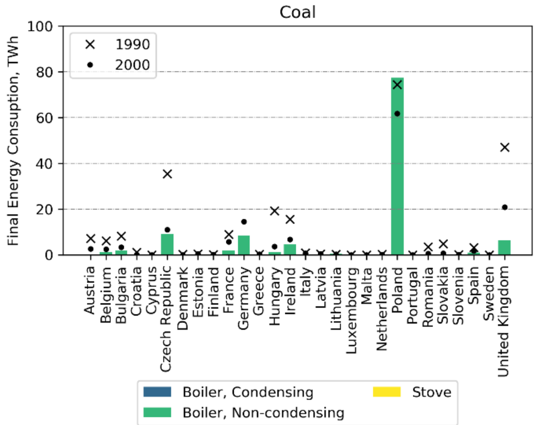
(**a**) Natural gas



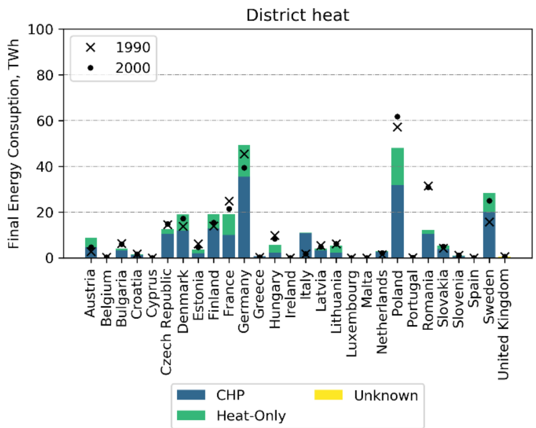
(**b**) Oil



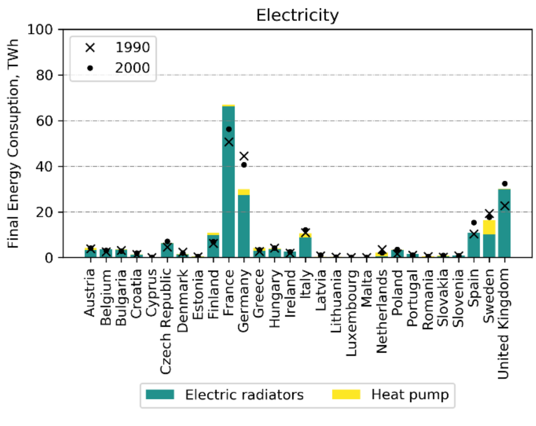
(**c**) Biomass



(**d**) Coal



(**e**) District heating



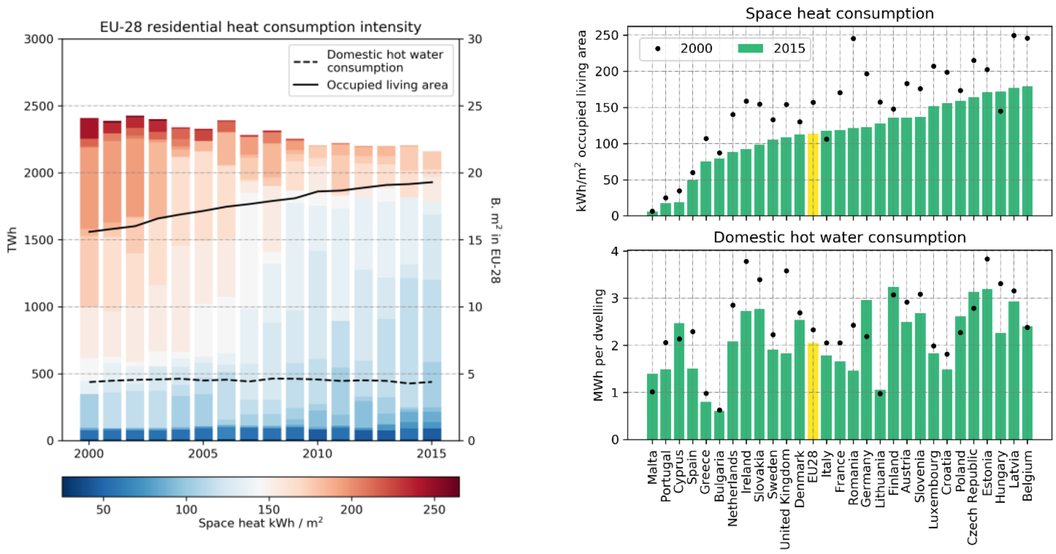
(**f**) Electricity

Figure 6. Final residential heat consumption for each EU-28 MS by type of end-use residential heat technology for (**a**) Natural gas, (**b**) Oil, (c) Biomass, (**d**) Coal, (**e**) District heating, and (**f**) Electricity. Note: (**a**) and (**b**) have a different x-axis scale than the remaining figures.

For biomass, France (93 TWh), Italy (79 TWh) and Germany (65 TWh) had the highest FEC among the EU-28 in 2015. The analysis show that Italy experienced a significant high growth in biomass consumption from 7 TWh in 1990, increasing more than 10-fold the FEC of biomass for residential heating. After these countries follow Austria, The Czech Republic, Hungary, Poland, Romania, Spain and The UK who all with a FEC of biomass above 20 TWh in 2015. Poland alone is the top consumer of coal for residential heating in the EU-28 with 77 TWh in 2015, 70% of the FEC of coal in 2015. Several other countries have managed to achieve large declines in FEC of coal for residential heating: Czech Republic, Ireland, Hungary, France and the UK all saw large declines in coal consumption. Germany and Poland had the highest DH FEC in the EU-28 with 49 TWh and 48 TWh respectively in 2015. Sweden follows with a DH FEC of 28 TWh, with Finland, France and Denmark all supplying 19 TWh of DH in 2015. Romania experienced a decline of 50% in the FEC for DH from 2000, the largest in the dataset for the large-scale collective heating infrastructures. Poland, Hungary, Czech Republic and France also decreased the FEC for DH during the 25 year period, while Austria, Denmark, Finland, Germany, Italy and Sweden expanded DH. As mentioned above, France was the highest consumer of electricity for heating at 67 TWh in 2015, with The UK and Germany both at 30 TWh.

4.5. Space Heat and Domestic Hot Water Consumption per Occupied Square Meter

Figure 7a show the development of residential SH consumption in the EU-28 split into shares of SH consumption intensity per MS average per occupied m^2 as well as the development of DHW consumption and total occupied living area in the EU-28. The EU-28 total residential SH consumption has decreased around 10% since 2000, from 2411 TWh to 2161 TWh in 2015, despite an increase in occupied living space as illustrated by Figure 7a. The EU-28 occupied living area increased 24% during the period, from 15.6 B. m^2 in 2000 to 19.3 B. m^2 in 2015. The DHW consumption remained steady just below 500 TWh per year during the period.



(**a**) (**b**)

Figure 7. (**a**) Development of EU-28 total residential heat consumption from 2000 to 2015 (left y-axis), split into MS average heat consumption intensity per m^2, and development of occupied residential living area (right y-axis). (**b**) Residential space heat consumption per occupied living area and domestic hot water consumption per dwelling for each MS in 2015 with a reference value for year 2000. MSs are sorted based on space heat consumption per occupied living area in 2015.

MS with high average SH consumption per occupied living area, above 250 kWh/m^2, overall decreased their SH consumption intensity per occupied living area to the range between 150 and 200 kWh/m^2.

The residential SH consumption intensities in 2015 ranged from Malta at 6 kWh/m^2 to Belgium at 179 kWh/m^2 in 2015 as shown by Figure 7b. While this represents a significant difference between the residential heat consumption intensities in the EU-28, there is also a number of MSs within a close range. Ireland, Slovakia, Sweden, United Kingdom, Denmark, Italy, France, Romania, Germany, Lithuania, Finland and Austria were all within ±20% of the EU-28 average residential SH consumption intensity at 113 kWh/m^2 in 2015, representing 70% of the total EU-28 residential SH consumption. MSs with higher residential SH consumption per occupied m^2 than 20% of the EU average could look into their building stock quality, residential housing renovations, control systems and heat billing, as these aspects could influence the higher SH consumption.

Figure 7b also illustrates that the average MS residential SH consumption decreased since 2000. Latvia had the highest average SH consumption per occupied m^2 in 2000 at 250 kWh/m^2, followed by Belgium and Romania both at 246 kWh/m^2. Latvia decreased the average SH consumption per occupied m^2 to 177 kWh/m^2 and Belgium decreased to 179 kWh/m^2 in 2015. Romania has made a significant improvement to 121 kWh/m^2 in 2015, cutting the average SH consumption per occupied m^2 in half compared to 2000 levels. The average MS decrease during the 15 years was 36 kWh/m^2, and in 2015, no MSs had average residential heat consumption intensities above 200 kWh/m^2. Italy and Hungary increased as the only MSs the residential SH consumption, but decreased in DHW consumption during the same period. Malta, Cyprus, Germany, Finland, Poland and the Czech Republic all increased their DHW consumption, while Bulgaria, Lithuania and Belgium remained at the same level in 2015 as in 2000.

5. Lacking Knowledge about Residential Heat Consumption and the Building Stock Quality

This paper has assessed the EU-28 residential heat consumption supply chain from PES to heat demand. Data for FEC was available for all EU-28 countries, with some instances of missing data. This allowed the estimation of PEC and distribution infrastructures. When assessing the parts of the supply chain within the building stock as the end-use technologies, energy demand, building age, renovations and quality, significant empirical knowledge gaps arise. These topics have received considerable attention from research efforts see e.g., [11,51], with the purpose of creating a detailed single year dataset or cost-curves describing renovation costs of existing building stock for forecasting and modelling work [41,59].

The actual knowledge about the current building stock and its historical development is scarce and with inconsistencies among dataset. Data about the historical development and quality of the EU-28 building stock makes it difficult to assess the building level efficiency regarding residential heat consumption. Increasing data collection about residential heat consumption is a task spread across several actors and multiple layers of government. While local governments and municipalities are important in the work with utilities, building developers and renovators, national governments must provide sufficient incentives and regulative frameworks to support data collection about residential heat consumption. The EU is already implementing such measures, in, for example, the EED [60] that promotes increased consumption based billing relying on measuring actual consumption.

In order to facilitate policy design for decarbonising residential heat supply, reliable and detailed data is important for decision makers, planners and researchers. Further research into the historical development and current status of the EU-28 building stock, heating demands and the connection with heating infrastructures forms part of moving towards low-carbon heat provision.

6. Discussion and Conclusions

The EU-28 residential heat supply show considerable need for a transition towards a decarbonized and efficient supply. Taking up 16% of EU-28 total PES at 17,875 TWh in 2015 [61], residential heating is an important subsector of the energy sector to decarbonise. 70% of PES for residential heating is fossil based, most end-use technologies are not state-of-the-art units and fossil fuel imports for heat consumption have increased since 1990.

Overall, large-scale collective heating systems using gas expanded from 1990 to 2015, while collective DH and electricity systems slightly decreased. The combined FEC for residential heating from collective heating infrastructures increased from 52% to 61% from 1990 to 2015. The only individual heating type that increased in market share was biomass, with an increase from 10% to 19% of the EU-28 FEC for residential heating between 1990 and 2015. While biomass is currently accounted for as CO_2 neutral and seen as a part of a RE supply for heating, it is still important to conserve and prioritize limited biomass resources for other energy uses in the overall energy system decarbonisation process [62].

Overall, the MSs residential heat supply display path-dependency and largely continue with established heat supply. Especially natural gas supply has been gradually expanded. Poland displayed a significant amount of lock-in from coal consumption, being by far the top consumer for residential heat and with no decline during the 25 year period. DH supply display a significant amount of lock-in, with almost all countries remaining at fairly stable levels, but with an overall EU wide decrease. Notable exceptions to the path-dependency effects exists, such as Italy, where individual biomass consumption increased 10 fold from 1990 to 2015, or Romania as an example of a country where DH infrastructure was rolled back by more than 50% since 2000. Ireland and The Czech Republic managed to make significant decreases in their coal consumption for residential heating. France, Germany, Italy and Sweden, among others, decreased oil consumption for heating.

The decline in coal and oil and shift to biomass indicate that incremental changes, such as changing fuels while maintaining the overall supply chain, is easier to accomplish and more widely used, than more disruptive changes such as changing from individual to collective supply.

The large-scale collective residential heating infrastructures display a coordinated planning effort from the MSs that have promoted these and which have resulted in large shares of residential heat consumption in certain countries.

The conclusions from this paper points specifically towards two use-cases. One, further research should continue to investigate path-dependency in residential heat supply and analyse more sources of lock-in and transition than was included in this study, such as institutional, political, domestic resources, behaviour or economic factors [25,32]. Empirical accounts of which factors produce path-dependency for residential heat supply could be important contributions to shifting towards renewables in residential heating. Second, by highlighting the path-dependent properties of existing infrastructures in residential heating, we highlight a topic that, to the best of our knowledge, is lacking from today's decarbonisation strategies for heating: the type of residential heating infrastructure and supply chains in the individual MSs will influence future developments towards decarbonized heat supply. To promote residential heating transitions in the individual MSs, this paper provides additional country specific figures of PES and FEC, in addition to those presented in this paper (Supplementary Materials).

There is both potentials for incremental upgrades in terms of replacing existing technologies with more efficient ones, but also for more radical changes such as new supply chains or collective infrastructures. Several studies show the potential for switching towards DH in high heat-density areas and to electric heating supplied by efficient heat pumps in low heat density areas [22,63]. Currently DH and electric heating account only for 10% and 8% respectively of the FEC for residential heating. Electric heating as a primary strategy for Europe can increase the strain on the electricity grids significantly as the magnitude of the heat demands compared to the current electricity demands is in the order of magnitude of a factor 2 to 4, and with a distribution over the year concentrated in the winter [4]. While individual heat pumps can decrease the peak demands and save expansion of electricity distributions grids and peak power plants [22], such strategies can be combined with more energy efficient buildings and DH [64,65].

Decarbonisation strategies should include two important points regardless of the infrastructural context. First, all residential heat decarbonisation strategies should be considered in relation to a long-term 100% RE system, to ensure that they comply with e.g., EU 2050 targets [3] and to avoid sub-optimization between energy sectors [24]. Second, all strategies need to include EE improvements both for energy supply and consumption while considering integration of RE [21,64].

MSs with DH infrastructures can leverage these to exploit heat sources such as geothermal, waste heat from industry, power production or large-scale heat pumps [22,23,64]. This will allow fuel supply changes to be made largely using existing infrastructures. A main challenge for existing DH systems is to lower supply temperatures to increase the efficiency of the network and give access to low-temperature heat sources [35,63].

MSs largely relying on gas grids should consider how these infrastructures fit into a future RE system. The historical trend from 1990–2015 has been to expand the use of natural gas in residential heating, and many MSs are currently locked into a largely gas fuelled supply regime. Gas grids could be repurposed either to supply flexible power plants [66], or for transporting green gases (biomethane, e-methane and hydrogen) for industrial purposes and transport as a part of the RE transition [67]. The potential for increasing the production of biogas to cover the natural gas use in industry, residential heating and power plants is though limited [68] and hydrogen is not proven to be a viable large-scale option for the heating sector.

MSs with high concentrations of individual heating should consider how to replace existing heating units and analyse potentials for collective heating systems. The EU's EED's article 14 on comprehensive assessments already mandate that such analyses be carried out [60]. Considerations of heat demand location and densities for evaluating the potential of collective and individual heat supply systems is crucial [65,69]. While the replacement of millions of individual boilers and stoves across the EU is a large strategic and governance task, transitions towards new fuel supply is possible in the residential sector as seen in the decrease of oil and coal for residential heating. While fuel shifts historically have been observed, it has been more difficult to find examples of radical supply chain shifts to collective large-scale infrastructures. Across the EU MSs, supplying 50% of FEC for heating with district heating and 50% with heat pumps in areas with low heat densities, combined with heat savings around 30–50% of projected heat demands have been shown as a cost-efficient approach [65,70,71]. This paper has shown that overall FEC for residential heating has decreased on an EU-28 scale, but the pace needs to increase to reach advised levels of heat savings.

Current rates of transition do need to increase to achieve a decarbonised residential heat supply in 2050, and the path dependency observed in EU-28 residential heat supply must be addressed. Overall, this paper has highlighted the scale of the transitions the residential heating sector faces towards decarbonized heating and the lock-in of different types of residential heating. While this paper has focused on the EU-28 MSs residential heat supply, the general arguments in this paper are likely also applicable to countries outside the EU. Being sensitive to historical infrastructural developments and their potential lock-in effects is important in many contexts of decarbonisation and countries aiming at developing low-carbon heat supply should be aware of their current technological situation.

It will entail ambitious policy design, strategies and investments to encourage shifting the current residential heat supply to new configurations. The analysis highlights the diversity of the EU-28 heat sectors in terms of PES, CO_2 emissions, distribution infrastructures, and end-use technologies and efficiency. The EU-28 MSs heat sectors have developed along different pathways to the current situations, resulting in diverse technological contexts. This is a crucial element to take into consideration when making strategies for heat transitions on an EU scale.

Supplementary Materials: Country specific figures for residential heating PES and FEC are available online at http://www.mdpi.com/1996-1073/13/8/1894/s1.

Author Contributions: Conceptualization: N.B., B.V.M.; methodology: N.B., B.V.M.; software: N.B.; formal analysis: N.B.; data curation: N.B.; writing—original draft preparation: N.B.; writing—review and editing: B.V.M; visualization: N.B.; supervision: B.V.M. All authors have read and agreed to the published version of the manuscript.

Funding: We thank the Horizon 2020 Hotmaps project (Grant Agreement number 723677), for partial funding for this work.

Acknowledgments: We wish to thank the anonymous reviewers for valuable feedback that improved the quality of this paper.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

Combined heat and power	CHP
District heating	DH
Domestic hot water	DHW
Energy efficiency	EE
The European Union	EU
Final energy consumption	FEC
Member State	MS
Odyssee-Mure	OM
Primary energy supply	PES
Renewable energy	RE
Space heating	SH

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Energy Research & Social Science 79 (2021) 102178

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Energy plans in practice: The making of thermal energy storage in urban Denmark

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ARTICLE INFO

Keywords:
Energy plans
Energy models
Sensemaking
Socio-technical transitions
Copenhagen
District heating

ABSTRACT

Much of the academic literature that investigates energy planning focuses on the development of plans but overlooks how they shape actors' situated sensemaking in the field. This paper followed the process of realizing a sector-coupling investment in a thermal energy storage in Copenhagen from 2017 to 2020. The analysis shows that while plans may help to define technological qualities and purposes, they do not always convince actors. Plans simultaneously close down technological uncertainty and open up others and through this cycle the energy planning process moves forward. The paper concludes by outlining new perspectives on the making and use of plans and provides recommendations for those who are participating in increasingly complex energy system transitions.

1. Introduction

Energy plans are central to energy transition processes towards low-carbon and efficient energy supply. They are made to inform, guide, and steer energy transition processes. For example, plans are acknowledged to provide insights for steering transitions [1], guide decision-making under high uncertainty [2], or promote alternative technological pathways [3]. This paper analyses how energy plans help to guide actors who are navigating uncertain and ambiguous energy transitions [4]. Actors in the middle of ongoing energy transitions need to make decisions while lacking knowledge about what effect their actions may have, and they, therefore, often turn to knowledge generation in order to reduce uncertainty, assess their options, or predict the consequences of their actions. While plans are used extensively both in scientific and professional energy planning communities, the way in which they are used has not received much attention. In order to address this research gap, this paper takes a novel approach by investigating how energy plans informed the sensemaking processes of actors investing in an innovative technology. This paper contributes to the existing energy planning literature by reflecting upon the actual use of plans, instead of assuming their usefulness in uncertain situations. This is achieved by way of a case study that follows the process of investing in a Thermal Energy Storage (TES), from it being outlined as one among many important technologies for low carbon energy systems to the final decision to invest in the TES.

Drawing on the existing perspectives on models and plans [5,6], we understand plans as narrative and calculative devices which, through their circulation among actors, build and maintain socio-technical imaginaries [7]. Concretely, several energy scenarios (e.g. business as usual, specific technological trajectories or ambitious policies) outline a number of possible development paths and are inscribed into energy plans [8]. These scenarios are generated by practitioners who, using energy modelling software, simplify and highlight certain aspects of reality [9]. Taking a pragmatic approach, this paper understands energy plans not as mirroring an outside and pre-defined reality, but instead, as actively contributing to creating it [10]. Energy plans can thus be understood as boundary objects, i.e., objects that are flexible and obdurate enough to allow coordination between actors [11]. For example, Taylor et al. [12] describe how the MARKAL energy model functions as a boundary object that enables communication between UK academic and policy communities.

The aim of energy plans is often to describe optimal system developments. They may include techno-economic designs for decarbonized national energy systems [13], ways to integrate intermittent electricity production across Europe [14], or outline a decarbonized worldwide energy supply [15]. While energy plans outline different technological pathways, the way in which these plans are applied in the 'outside world' is far from straightforward.

In this paper, the attention to how plans are used and their role in energy transitions is inspired by Weick [16]. Weick relates a story of a

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https://doi.org/10.1016/j.erss.2021.102178
Received 29 January 2021; Received in revised form 22 June 2021; Accepted 23 June 2021
Available online 1 July 2021

lost group of soldiers in the Swiss Alps who, luckily, find a map that helps them make their way back to camp. Once they have safely returned to camp, the soldiers realize that the map they used was actually not one of the Alps, but one of the Pyrenees. Weick [16] then concludes that, instead of simply prescribing geographical information, the map enabled the soldiers to generate action in particular ways which, eventually, stimulated them to return to their camp. He concludes that "*an imperfect map proved good enough*" [16]. Maps may stimulate emergent action in a specific context, provoking thoughts about what has happened and what should happen next. The map helped the soldiers find their way back, not by giving correct information, but by giving them belief in their actions, which stimulated reflexive action in reading the landscape and a sense of success. By analogy, plans can assist actors in situations of uncertainty because they provoke actions and set directions and not because they impose certain conclusions. Energy planners, modelers and practitioners often advocate calculating optimal solutions and use complex models that can capture the inherent 'reality' of a situation [17,18]. Instead, we argue that the use, potential efficiency, and ability to apply these plans does not merely depend on the accuracy of the plans in measuring an 'outside' reality. This argument is also supported by recent contributions to energy plans studies. For example, Ben Amer et al., in their study how Danish municipalities use energy models, show that the models are too complicated, too narrow, and lack synergies across energy domains when used in practice [19]. Taylor et al. argue that the MARKAL model facilitates communication across a number of actors, despite having a limited techno-economic focus [12]. Furthermore, other scholars have argued that municipalities may lack the resources and knowledge to comprehend and integrate complex models into their day-to-day planning activities [20].

Therefore, increasing the complexity, scope or boundary of energy plans does not equate to the successful realization of the conclusion and recommendations of a plan. Studies of urban energy planning show that even cities with ambitious energy plans fail to connect long-term visions with short-term action [21]. In a literature review of Strategic Energy Planning, Krog and Sperling [20] found that most of the literature focuses on technical aspects and neglects the implementation of technologies in real-world applications. Plans often promote specific paths of development, which may conflict with other proposals such as choosing between paths of new low-carbon supply or energy savings [22], or between centralized nuclear power supply and decentralized wind power energy systems [23]. Braunreiter and Blumer [24] show that energy scenarios are, broadly, either used as plausible futures or as data sources, but with a lack of guidance from the authors, scenarios can also be misrepresented when used. In other words, energy plans are not the result of objective engineering computations, instead they are intertwined with the specific purposes, agendas, analytical assumptions and discourses of their authors [25]. While not much attention has been given to the situated use of plans, there is growing recognition in the energy planning literature that plans work in more complicated ways instead of just following a linear path from the finished plan to the materialization of their conclusions.

This paper thus asks the following question: How do energy plans participate in energy transitions processes? In order to answer this question, this paper follows the investment process for a Thermal Energy Storage (TES) in the Greater Copenhagen District Heating (DH) system, from the publication of a national decarbonisation strategy in 2012 until the final investment decision in the TES in 2020. The paper investigates how several plans participated in the process of establishing the TES. In technological terms, TES is a rather simple technology; an area is excavated to make room for storing large amounts of heated water, which is then used in a district heating system. While the technology itself is not new, the organization, business model, usage and operation are challenging dimensions of the technology. Energy storage is a technology that has significant potential for energy system integration across sectors, achieving energy efficient and low-carbon supply [3]. Energy storage applications often need to engage with stakeholders in novel ways, which may require new partnerships to achieve adoption [26], or consider the practices of their users [27] to overcome social and cultural barriers [28]. Energy storage therefore might face different challenges compared to electricity generation such as wind turbines and photovoltaics, due to their new role in the energy system. The majority of the literature with social science perspective on energy storage either deals with electrical storage [29–32] or TES on a household level [27,28].

By using interviews and following the plans published, the paper follows the actors and their activities and traces the effects of the plans that promoted TES as a low-carbon and sector-integrating technology in Greater Copenhagen through three instances. First, a low-carbon pathway for the Greater Copenhagen DH system was outlined in a series of studies, in which TES was promoted as one among many solutions due to its ability to connect the electricity and heating sectors. Second, the operation of the TES in the Greater Copenhagen DH system was decided through energy system calculations and discussions about the specific use, qualities, and potential benefits of the TES. Third, the actors had to establish a viable business model for the new technology and split investment costs and benefits between the involved actors in the Greater Copenhagen DH system.

The paper is structured as follows: First, our theoretical approach to sensemaking in energy planning is presented. Section two outlines the methodological approach and the research design used for investigating how plans participated in this case of energy planning. The third section provides a general introduction to the Greater Copenhagen DH system. The main case is then presented, which is split into three sections. The article finishes with a discussion of the research and conclusions.

2. Sensemaking in energy planning

Sensemaking is the processes by which individuals and groups attempt to interpret, make sense of, and navigate novel, uncertain or ambiguous situations [16]. Processes involving innovation, strategy-making or "future-oriented" decisions are often characterized by several cycles of sensemaking and sense giving, in which members of the collective attempt to influence the common understanding of the situation [33]. As such, sensemaking processes may both entail processes at the level of the individual or the collective, whereby information, arguments and positions must be communicated and exchanged between actors [33].

A central notion in sensemaking is that action is required to produce knowledge [34], and that the inquirer can only learn about the object of inquiry by manipulating it [35]. Trying things out can be expensive, time consuming, if not outright dangerous and, therefore, energy planners, researchers, and scholars have developed epistemic devices, in the form of energy models, calculations and simulations, to be able to test their proposals, actions, and ideas before implementing them in real world applications.

Processes of sensemaking, therefore, depend on both the actors, their situations and the socio-technical equipment [36] such as the plans and other knowledge devices brought to the process to make sense of the situations [37,38]. Such dynamics in processes of knowing or sensemaking always shape actors whether they are lost (as the soldiers in the mountains), are making sense of uncertain situations or negotiating between different positions. Making sense of an object is a collective effort, which takes place between heterogeneous actors, all of whom have their own particular understanding of the situation [36].

Knowing an object requires establishing and bringing forward properties through measurements, analyses and judgements, which can be achieved by the use of analytical models, simulations, data and statistics [37,38]. A central point is that the qualities are not intrinsic to the technology but are instead constructed through the analytical model. Bringing a technology into being often follows the standard requirements used by planners to make its effects plausible but also to highlight its use within a socio-technical complex, e.g., defining the technology in legal, operational, economic, and material ways, taking into account specific knowledge, habits, and routines of the users [39]. These activities are not neutral as it is the analytical models and epistemic equipment that bring out the technological qualities in specific ways. For example, Garud et al. [40] show that nuclear power has been categorized as being *"emission-free", "un-safe", "too-cheap-to-meter"* and *"expensive",* depending on the methods used to describe the qualities of the technology. Similarly, in this paper energy models and methods are understood as being actively involved in generating knowledge about the objects, even if this results in different interpretations of the same technology [41,42].

The purpose of technological appraisal in processes of sensemaking can generally be described as either *opening up* for new inputs, discussions or viewpoints, or *closing down* processes to take decisions or produce agreements [43]. Therefore, making sense of a certain situation and how to act in it relies on knowledge and expertise, the specific socio-technical configuration, the specific type of question and uncertainty, and also how actors will attempt to resolve it and with what equipment. While processes that open up seek to involve new viewpoints and opinions, the aim of technological appraisal for closing down is to choose between options, advocate specific solutions or make suggestions. However, such conclusions are rarely stable for long, and can shift, change or produce new emergent effects [44,45].

The ability to reach closure among heterogeneous collectives of actors can be described as the convergence of a network [46]. Convergent networks gradually develop over time, during which common epistemic practices, trust, communication infrastructure and boundary objects are established and agreed upon. In contrast to weakly convergent networks, in which all practices, theories and knowledge production are contested, debated and are particular to the individual actors, highly convergent networks benefit from an agreement on common measures, calculation practices and a history of working together [47]. In highly convergent networks, all actors do not necessarily do the same task, but they are able to work across diverse disciplines such as economics, engineering, public policy, etc. towards the development of the socio-technical system [46]. Therefore, the outcomes of planning processes are not necessarily the result of rational, optimized paths that have been outlined in a scenario. Outcomes such as 'how to think and what to do with a technology' may be the result that emerges from sensemaking processes involving interaction and negotiation between actors with different understandings [48].

Therefore, our theoretical approach places epistemic devices centre stage in processes of sensemaking in uncertain situations. Actors seek to *close down* uncertainties by defining them in technical, legal, operational or economic ways, thereby producing different categorizations of technology. Such efforts take place in collectives of actors with their diverse understandings, objectives and epistemic approaches to uncertain situations. The ability of these socio-technical actor collectives to work together and coordinate efforts can be described as the convergence of the network. Convergent networks benefit from trust, long-time cooperation and a common language that enables coordination.

3. Research design and methods

Using a longitudinal case study approach, this paper follows the way in which plans are used in energy transitions [49]. The case study approach allows the researcher to explore phenomena in depth; it allows one to follow the actions *in medias res,* amid their unfolding [50]. With this research design, we could study how abstract challenges such as climate change and low-carbon transitions materialize in specific action "*on the ground*" [51]. Following the implementation process of the TES, a new technology, enabled us to explore the ways in which plans are mobilized and used by energy practitioners in situations of high uncertainty [52]. It allowed us to follow the struggles and controversies faced by the practitioners in their attempts to make the world known and actionable as it unfolded, whereas a retrospective historical analysis would only have allowed us to aggregate facts *a posteriori.* [53]. Therefore, the case study is a valuable approach as it can bring new insight into the challenges faced by energy practitioners at a specific time and place [54].

The research process stretched over a period of 4 years from 2017 to 2020. The research can be divided into three phases, which we term *exploration*, *continuation* and *follow-up*. In order to delve into the challenges faced by the implementation of the technology, 13 interviews were conducted from 2017 to 2020, which were supplemented by documents retrieved from different sources and at specific points in time. The next sub-section presents the ways in which the empirical materials were generated. The second sub-section presents how the data was analysed and the last sub-section presents the limitations to this approach.

3.1. Empirical data generation

The *exploration phase* took place during 2017. During this phase, we identified and mapped the DH practitioners involved in the project: the transmission utility VEKS, the DH utility HTF, the heat producers and energy consultants. Six semi-structured interviews were then carried out with the professionals. As the TES was a completely new investment, the interviews were designed to address the uncertainties and challenges confronting the actors. Interviews were conducted with directors, vice directors and energy planners at the transmission utilities, heat producers at utilities and waste incineration plants, the heat production scheduling organization and energy consultants. This first round of interviews enabled us to get an initial idea of the uncertainties and main difficulties and how these were related to the different actors' positions regarding the TES investment. During this time, new reports were also published by the DH practitioners [55], and these provided 'stabilized' information about the project. We then adjusted the design of the interviews to explore the role played by plans in reducing uncertainty, i.e., how they were actively used by the involved actors and why they were commissioned in the first place.

The research process gradually shifted to the *continuation phase* in 2018. During this phase, we kept track of the implementation project through secondary sources, email correspondence with the involved DH practitioners, and we conducted one interview. Furthermore, we followed the challenges faced by the actors in terms of agreeing on the business model. The expectation at the time was that their calculations would provide closure to the process, but in the end they did not achieve this alone. We were unable to gain access to the internal financial calculations due to confidentiality, which presents a limitation to this study.

This phase gradually led to the final decision about whether to invest in 2019 and 2020, the *follow-up* phase. During this time, we carried out six interviews, and we again adapted the questions in order to understand how the agreement to invest was reached and to summarize the entire process. Given the iterative nature of the interviews, which also influenced our own sensemaking process, the follow-up phase was important because it allowed us to verify the quality of the data collected and our own understanding of the field. Therefore, this helped us to validate our findings and conclusions.

The main empirical material in the form of interviews as well as an overview over the actors' role and equipment is summarized in Table 8.1 in the appendix. References to the interviews are given in text and the interview guides are presented in section 8.2 of the appendix.

3.2. Analysing data

Each of the semi-structured interviews was transcribed. The primary and secondary documents were read and searched for content on intended use, purpose, and specific methods of the energy plans. As the amount of empirical data was relatively limited, there was no need to use any coding programs. Instead, we chose to approach the generated material 'abductively', a method which "*alternates between (previous) theory and empirical facts (or clues) whereby both are successively reinterpreted in the light of each other*" [56]. Abductive work is based on rigorous empirical data combined with theoretical and methodological insights to facilitate understanding and the interpretation of the data. This approach allowed us to apply theoretical concepts in a research design solidly based on empirical material [57].

Consistent with Weick's sensemaking, the process leading up to the TES investment involved both shifts in our own sensemaking of the process, while following the sensemaking of the interviewees. For example, we did not know at the beginning that the sensemaking of actors using plans would be a finding that would be so important in the work of professional energy actors. This process allowed us to identify when actors either agreed or disagreed on certain topics, the voices existing in the field, and the different representations of a 'reality'. Once the main voices, controversies and interpretations had been identified, quotes illustrating the issues at hand were then highlighted, and the *final phase* was used to verify our conclusions with the practitioners in the field.

3.3. Methodological limitations

The most recognized limitation to the case study approach is its lack of generalizability [57]. The context in which the TES implementation occurred is specific to the Greater Copenhagen DH system, which limits the conclusions that can be drawn about the role of energy plans in general. This is discussed further in the conclusion of the paper.

Another limitation to the case study approach is that it can be difficult to define the relevant time period for longitudinal studies of energy transitions as they rarely have a clear start or end [58]. Research papers are also limited in length and can only cover a limited perspective. In this paper, the beginning was found through reference to the empirical material, and was chosen as the earliest mention of plans that informed the process. In the following section, we elaborate on the case and its historical development in order to provide some context. The end of research process was also determined through reference to the empirical material and was taken as the point when the final decision to invest in TES was taken. Nevertheless, as discussed below, such implementation and sensemaking processes are never truly completed.

The confidentiality of the calculations and the business models of the DH practitioners represent the final limitation. As they contain information that is regarded as trade secrets, we did not gain access to the actual contracts signed by the involved DH actors. Gaining access to decision making arenas is a challenge for social science energy research, and it needs to be an integrated part of the research design [59].

4. The background of district heating in Copenhagen: A system of pipes, plants, legislation, actors and organizations

During the oil crises in 1973 and 1979, DH began receiving increased attention from the Danish government, which instructed the municipalities to plan for their heat supply [60,61]. Since the introduction of the Heat Supply Act of 1979, DH has been regulated by a *True Cost* (*Hvile i sig selv*) economic principle [62], which stipulates that no profit can be made from heat production, transmission or distribution. Therefore, the utilities can only charge the *True Cost* of heat, including production, operation and maintenance, salaries, and investments. The Heat Supply Act also requires all investments in heat production units to be assessed based on a socio-economic analysis, which encompasses a systems perspective instead of a cost-benefit analysis from the perspective of the individual actors. The Danish Energy Agency provides the methodological and analytical basis for the socio-economic analysis [63].

The Greater Copenhagen DH system is relatively complex in comparison to most of the other Danish DH systems, which are predominantly operated by a single utility, responsible for production, distribution and billing [64]. Fig. 4.1 illustrates the transmission system operators and heat producers in the Greater Copenhagen DH system. In Greater Copenhagen, two transmission system operators (TSO), CTR in the East and VEKS in the West, are responsible for delivering heat from the large CHP and waste incineration units to their respective distribution companies, which send the heat to their customers.

District heating supplies almost 98% of the heat demand in Copenhagen [65]. In 2017, the DH production came from 5 CHP plants (69%) and 3 waste incineration plants (28%), with the remaining heat (3%) being produced by peak production units [66]. The voluntary collaboration, Varmelast ('Heat Load'), schedules the heat production among the CHP and waste incineration plants and peak production units. Varmelast is operated by two TSOs, Greater Copenhagen Utility and the heat production plants, and is staffed by a total of five employees from the TSOs and the utility [67]. The actors engaged in Varmelast agreed that a common organization for scheduling heat production would improve the overall system and benefit all involved actors. Varmelast is thus an example of a new organizational entity facilitating sector coupling and is the outcome of the long-term cooperation between the actors in the Greater Copenhagen DH system.

VEKS and CTR have been collaborating with the other actors to develop a common system since the 1970 s. They are tied together through materially connected infrastructure and are subject to common legislation and regulation, which suggests that a high level of expertise and know-how is present in the Greater Copenhagen DH system. A certain level of trust can be assumed to exist in the Greater Copenhagen DH system, as the Greater Copenhagen DH system has been gradually developed over the course of 50 years through cooperation between the two TSOs, the CHP plants, the waste incineration plants and the local utility companies. Cooperation between the actors manifests itself in several ways. The actors and their infrastructure are tied together through pipes, production units and pressurized heated water, and they have to coordinate the heat supply on a daily basis. The actors are also the subject of the same regulation, which introduced a common planning practice, i.e., the True Cost principle and socio-economic calculations. According to the interviewees, these factors contribute to the highly convergent nature of the Greater Copenhagen DH system.

5. Analysis: How plans participated in sensemaking processes

This section is divided into three analytical sub-sections, each of which covers an instance when plans participated in sensemaking processes. The three parts each present a different use of plans in energy planning and strategy making and are presented here in a chronological order.

5.1. Making a common future for the Copenhagen district heating system

Since 2009, VEKS, CTR and HOFOR (Greater Copenhagen Utility) have been working on the *Heat Plan Copenhagen* (HPC, in Danish: Varmeplan Hovedstaden), which has so far resulted in the publication of three plans. The aim of these plans was to analyse possible scenarios for developing the Greater Copenhagen DH system and to increase cooperation between the two transmission companies and the largest DH utility in the region, Greater Copenhagen Utility. The first report, HPC 1, was published in 2009 [68], and HPC 2 was published in 2011 [69]. The plans were primarily prepared to coordinate the long-term development of the regional infrastructure between the three actors who had commissioned the work, with a focus on security of supply, base load production units and the integration of renewable energy.

In 2012, the Danish Government's new Energy Agreement outlined the path towards a transition to renewable energy [70]. This provided a new framework for the HPCs. The Governmental agreement foresaw an increase in fluctuating renewable power production, increasing use of bioenergy and a move towards more integrated energy systems such as the electrification of the heating and electricity sector and smart

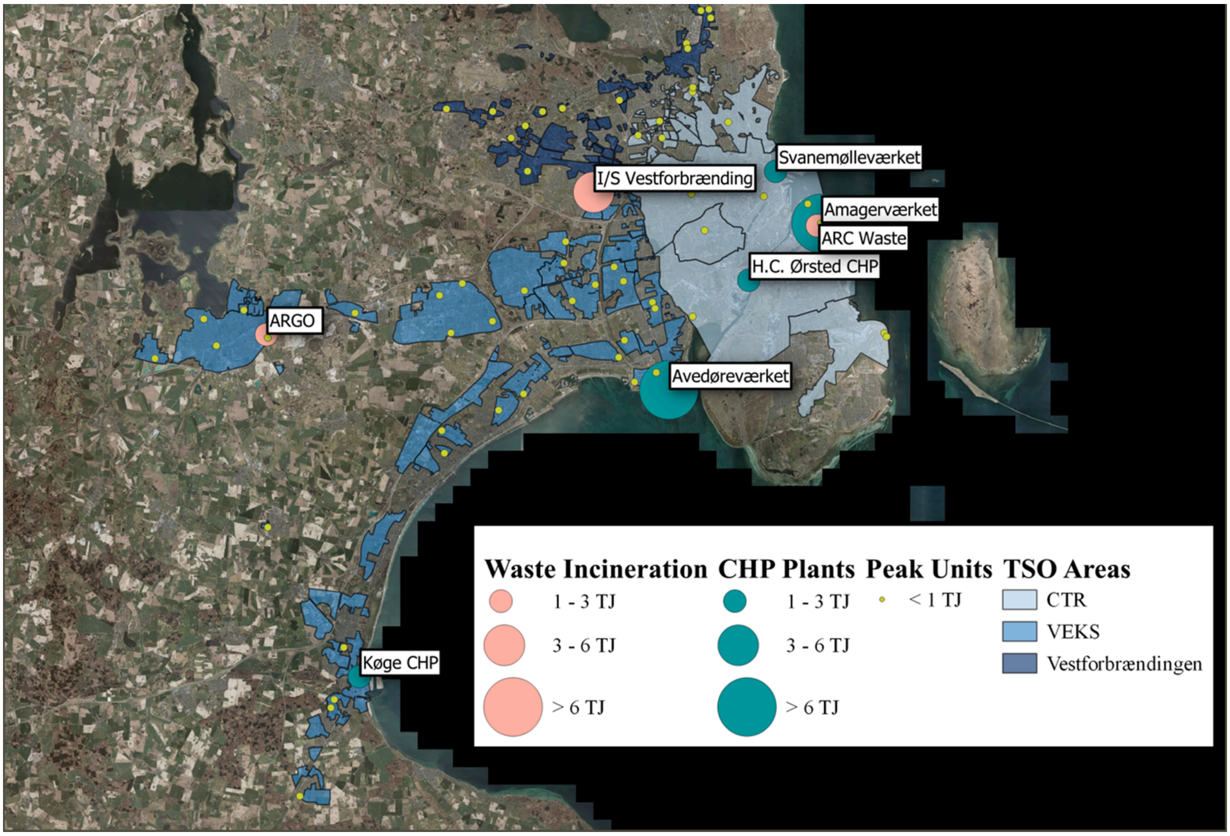

Fig. 4.1. Map of district heating plants and transmission system operators in Greater Copenhagen. Authors' representation based on data from the Danish Energy Agency (2017).

electricity grids [70]. The same year, the Municipality of Copenhagen set the goal to become carbon–neutral by 2025 [71]. These two plans raised the question of how the DH System could be adapted to be in line with the new low-carbon future set by the Danish Government and Copenhagen Municipality. The Danish Energy Agreement thus stimulated action in the Greater Copenhagen DH system: it set the direction towards decarbonized energy systems and prompted VEKS, CTR and HOFOR to calculate and make known how the DH could be decarbonized in time via the preparation of HPC 3.

Work on HPC 3 took place between 2012 and 2014. The plan was based on the new premise, derived from the Danish Energy Agreement, that the energy system had to be carbon neutral by 2025. Therefore, VEKS, CTR and HOFOR identified which investments and conversions were necessary in the short (2025–2030) and long term (2050). The three actors predicted a future with a high proportion of fluctuating electricity production and analysed the impact of this on the Greater Copenhagen DH system [72]. One of the main conclusions of the report was that it was necessary to increase the TES capacity by ten in order to increase the flexibility of the system and to accommodate an increased share of fluctuating electricity resources in the DH system [72]. HPC 3 demonstrated that the implementation of a TES could create the needed flexibility for the energy system to accommodate more fluctuating wind power production and that it could be beneficial for the overall economy of the system:

> *"The analyses indicate that thermal energy storage capacity of several times the current capacity may be economically well-founded. This should be analysed further."* [72]

HPC 3 demonstrated and concluded that an increased TES capacity was economically feasible, and that it would reduce the heat prices and CO_2 emissions. The HPC 3 plan participated in the sensemaking process to determine how the actors could decarbonize their production by identifying suitable new technologies and the necessary capacity needed. However, HPC 3 also left uncertainties as it did not specify who would gain from these investments or how the TES should be operated. These factors were to "*be analysed further*" [72]. Thus, while closing down uncertainties in terms of which technology was necessary for a low carbon future, the HPC 3 simultaneously opened-up and introduced new uncertainties for the actors in that it demonstrated that the TES was central to realizing the decarbonisation goals (closed down) but left room for uncertainties concerning how the TES should be operated (opened up) [43].

5.2. From multiple understandings of energy storage usage to a single operation strategy

The second instance of uncertainty among the actors was related to how the TES should be operated and who would benefit (and how much) from the technology. Three actors in the Greater Copenhagen DH system assessed how additional TES capacity could benefit their operation. Specifically, a DH utility wanted TES capacity in order to improve their power plant operation by allowing flexible electricity production (District Heating Utility 1 Interview 2017). Another DH utility envisioned TES capacity to store excess heat from district cooling production during the summer months (District Heating Utility 2 Interview 2017). Finally, a waste incineration plant wanted to store excess heat during the summer, when heat consumption is low, for the winter period when demand is higher (Waste Incineration Plant Interview 2017). The considered usages were tied to the respective actors' facilities, the technologies they used, and their respective means to increase efficiency.

The actors' socio-technical situation influenced their envisioned use of the TES and, consequently, several different understandings of the technology were present at this time of the process. The TES could potentially be used to store excess heat production from waste incineration or cooling production, integrate renewable electricity production, balance the Greater Copenhagen DH system, decrease peak production, or store solar thermal production for the winter months. Some of these uses were complimentary, while some were mutually exclusive. On the one hand, there is *seasonal storage* operation, whereby heat produced during the summer is stored for when demand is higher in the winter. On the other hand, there is *short-term storage*, following the production of the plant or the system, which stores or delivers heat when it makes sense from an economic or technical point of view.

In order to calculate and define which of the two possible storage uses would be the most feasible, VEKS and a DH Utility interested in TES capacity solicited two technical plans. The first report investigated the operation of the TES from an energy system perspective using the same approach as that applied in the HPC 3 studies, deploying the same models but developed further to focus on the TES operation and its benefits for the Greater Copenhagen DH system [55]. The second report was a project proposal for the municipality [73], which approves investments in DH infrastructure. We name the two plans the *TES Operation Report* and the *TES Project Proposal,* respectively.

As it was made by the same consultancy company the made analyses for HPC 3, the TES Operation Report adopted the same methodological approach as that applied in the HPC 3, which was widely accepted by the Greater Copenhagen DH actors. The report reached two important conclusions. The first was that only short-term operation was economically feasible for the TES. The second conclusion was that the storage should be used for the entire system and not for just one single actor. A consultant relates:

> *"It was an acknowledgment process, because the investment alone is so expensive that it would not be feasible to store heat from summer to winter. The only thing that would make the investment profitable was to use it together in the system" (Heat planning consultant Interview 2020, own translation)*

The report also emphasized that short-term operation was the most feasible use; the TES was to be operated as a daily or weekly storage. With such usage, the TES profits were calculated to be approximately €670,000 – €940,000 per year in total. These profits would be earned by the TSOs (55%), the CHP plants (24%), and the waste incineration plants (21%) [55]. The report thus grouped the different actors and companies into three distinct categories without specifying which individual companies would receive which benefits.

The second report, the TES Project Proposal, had to be approved by the municipality. Rather than being a single production unit, the Project Proposal categorized the TES as part of the system infrastructure to optimize operation, and not as a production technology:

> *"From fluctuations in the marginal production price in the district heating system, which in the future will become more and more dependent upon fluctuating electricity prices, it is expected that the storage will go through a cycle of charging and discharging on average every week. [...] The storage will therefore not be a heat producing unit, but a unit, that is contributing to optimize and improve the overall heat production."* [73]

The quote echoes both the HPC 3 with regards to the expectation that fluctuating production would increase in the future, and the TES Operation Report, which argued for short-term operation. By categorizing the TES as a part of the system infrastructure, the report transformed the TES from a stand-alone technology, operated and owned by a single actor, to a common piece of the regional infrastructure to be owned and operated in collaboration. The two reports classified the storage as a new piece of system infrastructure, operating on a short-term basis to manage fluctuations in the energy supply, and located within easy access of the transmission and distribution network. This categorization rendered the project feasible for the entire system and thereby transformed the TES that was to be brought into being.

It can be concluded from this instance that energy plans are instrumental in sensemaking processes that shape energy transitions. In this instance, the TES was re-categorized from a stand-alone technology to a piece of system infrastructure. Categorization work [40] was important in determining the use, technological benefits and operation of the TES.

By closing down the operation uncertainty and categorizing the TES as system infrastructure, a third question opened up: how to split the benefits and divide the investment costs between the different actors? The actors were now in a situation where they had agreed to establish the TES together and use it to increase system operation, as this would also benefit the individual actors. By shifting production from peak units to CHP plants, the TSOs could potentially reduce fuel costs by decreasing peak production and the CHP plant owners could potentially increase their production. Establishing the TES as a technology for system optimization opened up a new uncertainty: how the benefits achieved on a system scale could be translated into specific benefits for the individual actors and, conversely, how the investment costs of the TES should be split. While the TES Operation Report [55] outlined how the benefits would be split between the actors, categorized as TSOs, CHP plants and waste incineration plants, how to distribute the profits between the individual companies was not addressed.

5.3. Plans and calculations informing negotiations

Closing down the question concerning the TES operation opened up new uncertainty in terms of the benefits for each individual actor. As the Greater Copenhagen DH system consists of two TSOs, five CHP plants and three waste incineration plants, there was still significant uncertainty about who would receive the economic benefits derived from a TES. The task of modelling or calculating such results with sufficient precision proved difficult. Accordingly, the actors experienced difficulties in calculating how the investment costs should be split between the actors As illustrated by the following quote from a DH utility employee:

> "What does it mean if the storage gets more or less heat, if the costs increase or decrease, or to whom they can sell heat to? It is difficult to see if [our CHP plant] will gain any benefits. Perhaps some, perhaps nothing. And that is the same for all the actors" (*District Heating Utility 2 Interview 2017, own translation*)

As explained by the practitioner, it was difficult for them to determine the benefits for each individual actor with sufficient certainty. Due to the number of producers, the size of the network, and seasonal and yearly variations in production, among other factors, it was difficult to calculate exactly the benefits of a TES for each actor in the Greater Copenhagen DH system. Furthermore, because of commercial interests and regulations, there was no common data on the different units' earnings and operation of the DH system. The plant owners, utilities and TSOs all had detailed knowledge of their own units, but these details were not shared as they are regarded as trade secrets. Conversely, different assumptions and forecasts were used when estimating the effects of the TES:

> *"The [electricity] price is extremely important and they each have their electricity price forecast, as an example." (TSO 1 Interview 2018, own translation)*

Therefore, the actors used different analytical assumptions and models to estimate their respective benefits from the TES, which made it difficult to reach a common agreement about how to split the investments. "Splitting the bill" for the TES proved to be a negotiation based on arguments derived from energy system calculations about who would receive the benefits from the investment. For example, in the following, an energy planner from a TSO explains how energy models were used in the sensemaking process:

> *"Yes, through model calculations. Assumptions and long-term forecasts for the next 20 years and some sensitivity analyses, and then we decide on a reasonable place. Then we show the actors our calculations for their production units, we discuss the results with them, we see if they can recognize them, and thus that a storage would have the calculated effect on their production units as intended." (TSO 1 Interview 2018, own translation)*

This quote demonstrates the importance of the assumptions behind the energy model calculations, as well as the difficulty in determining the benefits of the TES. Although the calculations and energy models were central to the collective sensemaking process, it was difficult to reach a common understanding based solely on them. Instead, another dimension of the technology helped move the process forward. Supplying the TES directly from the transmission system entailed high temperatures for longer durations in the storage, which could potentially damage the storage liner. In 2018, the TSO, together with the utility company, energy consultants and a Danish university applied for a research grant to, "*demonstrate a 70,000 m^3 pit thermal energy storage in a new function as an accumulation tank in a district heating system with combined heat and power production from biomass and waste*" [74]. The project received €1.8 m to test the operation of a TES with such a liner in an energy system with CHP and waste incineration units examining how to create synergies between the heating and electricity sectors [74,75]. While offering financial support for technological development, the fact that it was a demonstration project meant that several actors not only saw it as a financial investment, but also as the development of new technology:

> *"There are calculations that showed some different percentages [of received benefits], but we could agree to 56% of the share of saved peak load, although other sensitivity analyses showed around 53%. Because this is a demonstration project." (TSO 1 Interview 2018, own translation)*

The new categorization of the TES as a *demonstration project* re-set the negotiations; being part of a demonstration project resulted in a degree of tolerance among the involved actors as to their expected benefits. The research grant facilitated the sensemaking process. It was easier for the actors to accept a degree of uncertainty with a demonstration project compared to a 'normal' project.

Accordingly, reaching an agreement about how to share the benefits and divide the investments costs of the TES relied on three factors. First, the negotiations were based on energy system calculations. While the calculations could not be used to determine how the costs and benefits should be split, they did provide a basis for sensemaking and deliberation. Second, the label of a demonstration project introduced a certain degree of flexibility to the negotiations. Third, still not able to agree completely on how to share the costs and benefits, it was decided that a follow-up group would monitor the TES operation after it had been built. This allowed all the involved actors to follow how it would actually operate in reality and facilitated ongoing discussions about who would receive which benefits.

6. Discussion: What was the role of energy plans in the sensemaking process?

We argue that the ways of knowing that are enabled and circulated by energy plans influence the way actors make sense of otherwise uncertain processes or technologies. Plans enable actors to investigate different courses of action and their consequences and simultaneously shape the results.

The analysis shows the epistemic role of plans in three instances of sensemaking in the establishment of a TES in Greater Copenhagen. First, uncertainty emerged from not knowing how the existing DH plants, units and infrastructure could be part of a decarbonized energy system, partly due to the emergence of national energy plans that outlined the need to increase renewable energy. The HPC 3 report outlined an energy scenario whereby the Greater Copenhagen DH system could use existing investments and infrastructure to achieve a low carbon energy system. To realize this transition to a future energy system with increased fluctuating electricity production, the HPC 3 highlighted the importance of increasing the TES capacity, thereby closing down uncertainty about how a future energy system ought to be. By outlining a national pathway to low-carbon energy supply on a national scale, the Greater Copenhagen DH actors had to consider what role they would play in this transition.

Second, promoting TES capacity as a way to transition the Greater Copenhagen DH system to a low-carbon energy supply raised questions about how the TES should be used and operated. Energy plans, solicited by a TSO and a utility company, concluded that short-term operation would generate the greatest benefit for the entire system by integrating fluctuating electricity production, and reducing peak boiler production. This process re-categorized the TES from a stand-alone technology owned by one actor, to a shared piece of the DH infrastructure. It also closed down the question about whether the TES should be used as short-term storage or seasonal storage. Third, closing down the question regarding how the TES should be operated resulted in the emergence of a new question; the short-term system operation meant that the investment costs had to be shared between all the actors in the system, which opened up the question of how to split the investment costs and benefits between the actors. The actual benefits of the TES could not be known until it was in operation and, therefore, the share of the benefits and investment costs had to be negotiated based on estimations and calculations. The negotiation of sharing costs and benefits was aided based on an understanding of the TES technology as a demonstration project, using an energy system model to simulate the technology operation and lastly by implementing a follow-up group that could monitor the project.

In the three instances, the TES was categorized in different ways that brought out and highlighted its use and qualities. Concretely, categorizing the TES as a technology that facilitated sector-integration and reduced peak loads positioned the TES as an important element in a low-carbon energy system. Again, the categorization of short-term system operation was framed as the most feasible way for the entire system to build and use the TES, thereby engaging the actors to realize the TES together. Categorizing the project as a demonstration encouraged investment of the behalf of the actors, who could tolerate greater uncertainty. These categories were important throughout the process in that they made the TES known and demonstrated its qualities as well as the problems it could solve. The analysis also shows that categories are not fixed entities but are instead always in the making and brought out through the work of the actors.

Furthermore, the analysis shows that many factors besides the plans themselves helped persuade the actors to invest in the TES. First, the fact that the convergence of the Greater Copenhagen DH system had been developed for many years through collaboration between the actors meant that they were used to working together and a certain amount of trust existed. Processes of sensemaking drove how actors closed down their uncertainties and energy plans played an important role in doing so, but they did not work alone. Collective sensemaking, in the form of negotiations, discussions and meetings was important to promote a common understanding of the TES. An important part of promoting this common understanding was the trust and long-time cooperation between the actors in the Greater Copenhagen DH system. Without this convergence, the energy planning process and collective sensemaking might not have been so effective. Second, the categorization of the TES as a *demonstration project* helped introduce some tolerance into the negotiation process in terms of expected profits. Third, while the energy plans made many facts known about the TES, they did not work in all cases. The energy calculations did not make the share of benefits and investment costs known with sufficient certainty, and the actors had to find other solutions. In this case, a follow-up group was formed to monitor the TES operation and see who would actually receive which benefits. While energy plans and their knowledge-producing machinery of energy models were only one part of the TES investment process, they proved invaluable tools. They decreased uncertainty and answered the questions posed by actors. However, the effectiveness of the energy plans was not due to their accurate representation of reality, instead they worked by bringing the TES into being in a way that made sense to the actors. Instead of searching for optimal solutions for application in an external reality, energy plans and models can begin to explore how they participate in co-creating these particular realities themselves.

The three instances of solving uncertainties reveals a continuous cycle of sensemaking of closing down and opening up [43], where each instance of closing down one uncertainty opens up another. This continuous process of opening up and closing down highlights a characteristic of energy plans, which is that they do not work in a vacuum, but built on each other. Each new energy plan analysed in this study was based on a previous plan. Energy plans can be said to work in relays, where they each answer their own formally administered task, but also ask new questions. As this opens up new questions about how to proceed next, new plans are needed. As such, a conclusion or statement is temporal, and new concerns may emerge and challenge closure. Still, the plans were effective when they built upon the conclusions of past plans, used the same methodology or the same assumptions. The *TES Operation Report* [55] used the same analytical equipment as that used in the HPC studies [72], assumptions about increasingly fluctuating electricity were used in several reports, and the conclusion about using the TES as a system storage informed the investment negotiations.

Fig. 6.1 illustrates this continuous process of closing down and opening up new questions in energy planning processes. This study thus provides new knowledge as to how energy plans can be used to solve uncertainties in energy planning. Plans do not linearly solve the actors' uncertainties, instead they enable the actors to engage in sensemaking processes. Although the plans facilitated understanding and shaped the understanding of the TES they did not work alone. The mutual trust, the long-term cooperation between the actors and agreement about a common goal, i.e., to develop the Greater Copenhagen DH system, were also central to achieving the TES. This finding is of relevance to energy planners, municipalities and governments as it highlights the need for establishing and maintaining planning environments with a high convergence among stakeholders, regulation and responsibilities where communication and coordination facilitates a collective endeavour to develop energy system infrastructures. The processes of closing down and opening up uncertainties highlights how such energy plans engage in continuous cycles of sensemaking.

7. Conclusion

This case has demonstrated how energy plans were able to translate future visions about a decarbonized energy system into a concrete investment in the form of a TES in the Greater Copenhagen DH system. It is a case where long-term vision and short-term action were connected to realize a low-carbon investment in an urban energy system, through several iterations of sensemaking. The actors commissioned plans to answer their questions, gradually closing down uncertainties about their situations. However, the dynamic process of sensemaking is not linear. While these plans effectively closed down the questions posed in the reports, they also produced new emergent questions, thus opening up new uncertainties. Continuously closing down questions as they emerged helped move the process forward towards an investment in TES capacity in the Greater Copenhagen DH system, but it also kept opening up new questions.

Plans were commissioned to close down uncertainties and answer questions for the actors. The plans did this effectively throughout this case by outlining what a decarbonized future might look like and the role of TES in this, describing how TES capacity could be used and operated and determining how the different actors should split the TES investment costs between them. This shows that the plans and their conclusions, in general, were adopted and informed the sensemaking of the actors. While the plans were effective in steering the process, they did not do so alone, but also benefitted from actors who had worked together on developing the Greater Copenhagen DH system for many years, developing know-how, expertise and trust.

The energy plans worked under a number of conditions. First, they answered relevant questions for the actors, who either wanted or had to change their situations. Therefore, the plans helped the actors out of situations of pressure. Second, the plans envisioned active roles for the actors to their own benefits. For example, the HPC 3 investigated how the actors could utilize their existing infrastructure in a decarbonized energy system. It was important to make plans that aligned with the interests of the actors. Third, the plans analysed and categorized some of the different ideas, opinions and understandings of the actors that already existed. This included the question whether the storage should be seasonal or short-term, or if it should be used by a single actor or as a piece of system technology. The plans made an arena where such uncertainties and disagreements could be debated. Fourth, the plans themselves worked in relays, building on past agreed methods, assumptions, and findings. Therefore, they created effective arguments based on previously agreed decisions and findings.

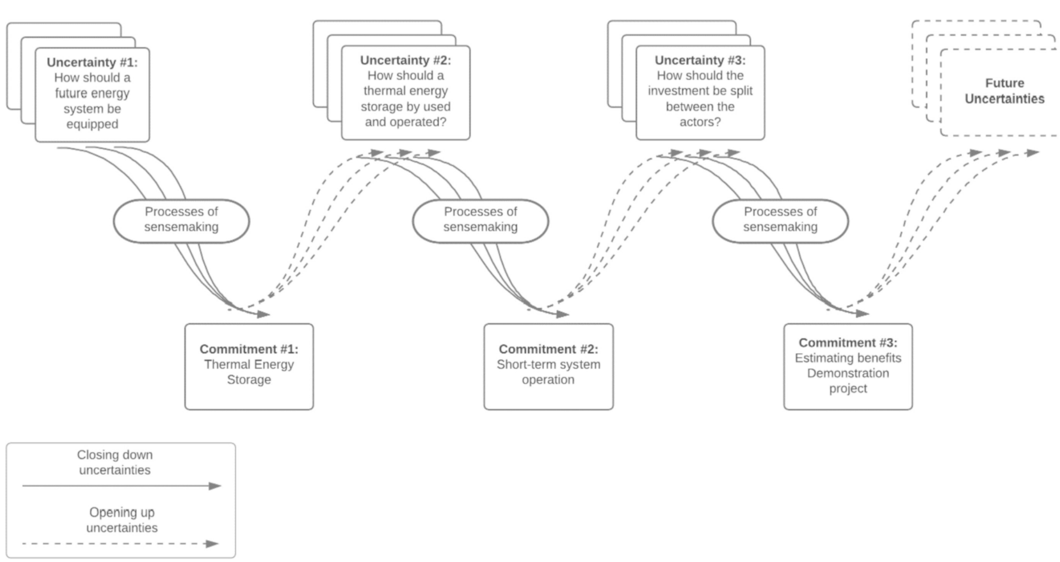

Fig. 6.1. Illustration of the continuous process of closing down and opening up questions in an energy planning process.

This paper has presented a case study of how an investment in TES capacity was realized in the Greater Copenhagen DH system. As with all case studies, it is particular to the specific situation in which the study was conducted. The way the investment was achieved, the business model, and the defined operation of the TES are all specific to this case. Therefore, a significant limitation of this study is that we cannot present a simple model or description of how to realize new investments in sector-coupling infrastructure in the future. However, the case shows some general relevance for energy planners, practitioners and researchers. First, the importance of cooperation, communication and being able to discuss different technical pathways and configurations was central to realizing the investment. A central conclusion for energy planners and practitioners is the importance of making plans that carve out specific roles and responsibilities for actors, close down uncertainties, while also being able to rely on convergent networks of stakeholders that facilitate cooperation and collective development. Second, as energy systems become increasingly connected between sectors, more investments are needed that transcend energy sector borders. This will likely result in new organizational, economic, institutional or regulatory challenges. Third, energy plans are effective tools, but they do not simply result in the materialization of their conclusions.

We hope this study will invite more researchers to investigate the question of how planners, decision makers and policy makers use plans in their work to promote low-carbon and efficient energy systems.

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.

8 Appendix.

8.1. Overview of actors and main empirical material

Table 8.1
Main empirical material from interviews and reports. Interviewees are kept anonymous.

Actors	Main role	Main technological equipment	Year of interviews
Transmission System Operator 1	Responsible for buying and transporting heat from CHP and waste incineration plants to district heating distribution companies	Owns the transmission network in their area Owns small heat production units	2017, 2018, 2019, emails 2019
Transmission System Operator 2	Responsible for buying and transporting heat from CHP and waste incineration plants to district heating distribution companies	Owns the transmission network in their area Owns small heat production units	2019, 2020
District Heating Utility 1	Distributes heat from the transmission system to their customers	Distribution infrastructure Small production units	2017, 2020
District Heating Utility 2	Distributes heat from the transmission system to their customers. Owns a large CHP plant	Distribution infrastructure CHP plant	2017
Waste Incineration Plant Interview	Handling municipal waste through incineration. Heat production an outcome of waste handling	Waste incineration plant	2017, emails 2020
Varmelast	Responsible for the day-to-day planning of heat production Voluntary cooperation between the main actors	Optimization tools Mathematical models	2017, 2020
Heat planning consultants	Providing inputs and expertise Make plans and calculations	Optimization tools Mathematical models	2017, 2020

8.2. Interview guide

8.2.1. Exploration phase (2017)

Can you tell about the reasons for investing in Thermal Energy Storage?

- What are the main benefits for you in investing in Thermal Energy Storage?
- How do you calculate the value for you – and with what tools, methods and categories?
  - o How do different ownership models affect your benefits?

Thermal energy storage specific questions

- What kind of technological solutions are you looking at (pressurized, non-pressurized, temperature, other?) – and why/what are the main challenges and benefits?
  - o Are you looking at collective solutions, e.g., system investments or storage for your own benefit and operation?
- What are the benefits for you – both operational, technical and economic? And how will you operate and use the storage?

Business model

- What might a business model for facilitating the investment look like?
- Who are you cooperating with?
- How does it affect the value (for you and the system) depending on whether it is a system or individual owned storage?

8.2.2. Continuation and follow up phase (2018 – 2020)

Can you describe what happened in the process the last year?

- New knowledge? How did you (and others) come to new understandings and agreements?
- What main challenges have you encountered? E.g. technical, organizational, investment-wise or regarding cooperation?
- What was unknown, uncertain and difficult?
- How is this new knowledge tied to the making of knowledge and the circulation of plans?
- How (with what measures) has agreement been reached?
- Is it still the same actors and stakeholders who are engaged?

Technological questions and deciding on the use of technology

- Did you decide on how to deliver back to the transmission network?
- Did you decide on how to use the storage (system vs individual) and which time horizon (short term vs seasonal)?
- What are main problems now?

How do you see the investment being shared among actors (if collective investment)?

- What is unknown, uncertain and difficult

- How do you see yourself and other actors overcoming these challenges?
- How – specifically with what tools, methods, knowledge and plans – do you create closure among the stakeholders and overcoming challenges?

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Energy Efficiency
https://doi.org/10.1007/s12053-021-09975-8

ORIGINAL ARTICLE

Implementing large-scale heating infrastructures: experiences from successful planning of district heating and natural gas grids in Denmark, the United Kingdom, and the Netherlands

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Received: 23 December 2020 / Accepted: 26 June 2021

Abstract Large-scale heating infrastructures in the form of district heating have significant potentials to increase energy efficiency and integrate renewables in line with the Paris Agreement and EU targets. Such infrastructures face challenges due to high investment costs, monopoly situations, regulation, and ownership and are often not supported by status-quo market regimes. This paper investigates how Denmark, the United Kingdom, and the Netherlands achieved high market shares in their heat supply using large-scale infrastructures between 1950 and 1980. The analysis investigates the drivers, actors, organizations, ownership models, financing, policy, and regulation that was involved in implementing these large-scale infrastructures. The findings illustrate how global events such as the oil crisis in 1973 promoted the need for concerted action. The infrastructures were realized through significant government intervention, coordinated work including repurposing existing infrastructure and actors, deploying new regulations, subsidies, and business models. The conclusions reflect on contemporary heat transitions towards renewable energy supply and how historical lessons are relevant for socio-technical transitions today. New heating infrastructures in the form of district heating should be built according to the specific local conditions, through a combination of government support, new regulatory tools, appropriate business models for recirculating funds into new investments, and by engaging existing actors into developing the new supply systems. Achieving high market shares of large-scale heating infrastructures is not business as usual, but requires significant adjustments in all aspects of energy systems.

Keywords Energy infrastructures · Socio-technical transitions · District heating · Gas grids · Energy planning

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Introduction

The European targets on climate neutrality and measures to meet the Paris Agreement require significant changes in all parts of the current energy system. One important part is heat consumption, which accounts for ~ 50% of the EU-28's energy consumption (European Commission 2016; Pezzutto et al., 2017). To decarbonize energy supply, heating must both increase efficiency and switch to low-carbon sources (Bertelsen & Mathiesen, 2020; Connolly et al., 2014; Drysdale et al., 2019). Studies show that district heating (DH) systems can improve overall energy system efficiency by exploiting excess heat from power stations and industry as well as from renewable sources such as geothermal, large-scale solar thermal, or sustainable biomass (Lund et al., 2010; Möller et al.,

2019) and could cost-effectively supply around 50% of EU heat demand (Paardekooper et al., 2018). DH systems can therefore be an important part of energy efficiency first strategies by accessing and utilizing otherwise wasted thermal energy, as recognized in the European Commissions Strategy on Heating and Cooling (European Commission 2016).

The significant increase in DH supply requires vast investments in distribution and transmission networks to transport the heat energy from the place of production to consumption. These large-scale network infrastructures are characterized by high up-front costs combined with long-term investments with long lifetimes resulting in monopoly market situations (Bolton & Foxon, 2015). DH networks thus pose technical potentials for decarbonized efficient energy systems but face significant implementation challenges concerning financing, ownership, and public governance and regulation (Lund, 2018; Lund et al., 2018). To learn about how large-scale DH grids have previously been implemented, a comparative analysis with the construction of natural gas (NG) grids has been carried out. We argue that while DH and NG systems differ in the energy medium supplied (gas vs. heated water) and the potential end-uses,[1] both types of energy infrastructures are capital intensive, have long lifetimes, and constitute monopoly situations. Regardless of their importance in modern societies, the socio-technical configuration and development of these infrastructures remain under-researched (Bolton & Foxon, 2015). This paper aims to investigate how such large-scale infrastructures have been implemented historically to inform how future energy-efficient large-scale infrastructures can be implemented.

We wish to add to the growing body of academic literature on heat planning and transitions by exploring how and under which conditions large-scale infrastructures for heat supply historically have been implemented. It is widely acknowledged that status-quo regulatory, market, and governance regimes are ill-equipped for technological change and development (Cherp et al., 2018; Turnheim et al., 2015; Unruh, 2000). Energy transitions broadly encompass processes of change in energy systems, including changes in primary fuels, production, or consumption (Sovacool, 2016). To understand under which conditions transitions can happen and when they are inhibited, it is useful to understand technology and infrastructure not merely as material, but as socio-technical systems (Smith et al., 2005). Socio-technical systems are configured by technology, organizations, regulation, knowledge, practices, and institutions; all factors that co-influence the development and pathways of the socio-technical system (Unruh, 2000). Heat supply transitions have been analysed before, notably with Gross and Hanna (2019) arguing for significant path dependency in heat supply systems. Heat decarbonization is often seen by policymakers as difficult, disruptive, and uncertain (Lowes & Woodman, 2020), both influenced by household practices (Hansen et al., 2019; Van Overbeeke, 2001), policy and regulation (Bürger et al., 2008; Connor et al., 2013; Hvelplund et al., 2019), ownership and financing (Hvelplund & Djørup, 2019), and planning competencies, tools, and practices (Ben Amer et al., 2020; Späth & Rohracher, 2015).

Denmark, the United Kingdom (UK), and the Netherlands were selected based on the categorization of EU-28 residential heat supply sectors in Bertelsen and Mathiesen (2020) as three cases to represent successful implementations on a national scale of large-scale infrastructures used for heating. These establishments of monopolies and their associated economies of scale were formed as a result of the energy and resource planning challenges and opportunities of the time. The UK and the Netherlands present two cases of reaching significantly high market shares of NG in residential heat supply, respectively covering 75% and 90% of residential final energy consumption for heating (Bertelsen & Mathiesen, 2020). Denmark is a case where DH infrastructure expanded to supply 90% of multifamily houses and 40% of the single-family houses in 2018 (Statistics Denmark, 2020a). The lessons drawn from these transitions can inform policymakers and decision takers about how past large-scale infrastructures were built and how new ones can be implemented.

Methodology

While historical research cannot predict future developments, studies can inform forward-thinking

[1] While district heating end-uses are limited to space heating and domestic hot water consumption in residences, natural gas can also be used for cooking and lighting.

decision-making and policies by pointing towards the often complex connections between technical systems, regulation and policies, and societal and cultural understandings of energy (Hirsh & Jones, 2014). In hindsight and if not careful, historical transitions can often look like unavoidable, straightforward, and linear developments (Hanmer & Abram, 2017). Sovacool (2016) advocates that historical research of energy transitions take a broad view of the developments during the period covered, while also being sensitive to the particular conditions under which solutions appeared, and equally important, under which conditions uncertainty was present about potential paths of development.

DH and NG systems can be understood as large technological systems (Hughes, 1987; Sovacool et al., 2018; Van der Vleuten, 2004). Large-scale infrastructural systems are socio-technical, configured by social, political, economic, and professional aspects. Hughes (1987) gave the following definition: "Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping". Large-scale infrastructures such as NG and DH grids have long lifetimes, the initial high investments translate into significant sunk costs and tend to be monopolies, and their services are often essential to everyday life, such that they verge on common goods (Bolton & Foxon, 2015; Hughes, 1987). Economies of scale (Unruh, 2000), expected market failures (Künneke, 1999), and practical experience of governing the systems (as we will present in the UK case below) meant that these network infrastructures are often treated as monopolies by regulators.

Studying the development and change of large-scale infrastructures means analysing the development of how incumbent infrastructure and the related organizations and actors change. Much of the transition literature is focused on how novel technologies can disrupt and change incumbent regimes (Geels, 2002; U. Jørgensen, 2012; Schot & Geels, 2008). Instead, this paper analyse the development and change of incumbent grid infrastructures and how they remained relevant through changing socio-technical configurations. This engages with the call from Turnheim and Sovacool (2020) to look more directly at incumbency and to explore how incumbents can participate in transitions (Berggren et al., 2015).

Following Miller and Rose (2008), problems and their solutions are the results of the rationalities that form part of defining governance processes. Technological categories such as *energy-efficient*, *sustainable*, or *polluting* all describe the problem-solving abilities and participate in determining the relevance of the technology or infrastructure in question (Bowker & Star, 1999). These categories endow the technology in question with certain qualities and participate in the struggles of determining whether the technology is relevant as a problem-solver. These qualities are not inherent in technologies, but are "materially anchored, yet institutionally performed, socially relevant, and entrepreneurially negotiated" (Garud et al., 2010, p. 54). The argument that qualities are not inherent traits in the technology but created through engagement with society, gives attention to how the seemingly same material infrastructure can change meaning and purpose in society through history. Following Hughes's (1987) original definition and that large-scale infrastructures are essential to societies and everyday life (Bolton & Foxon, 2015), this paper explores how such infrastructures became and remained relevant societal problem-solvers.

Analytical framework

Four main dimensions were chosen to shape the questions and focus of this article based on the literature introduced above. First, the drivers and qualities of the infrastructures were followed to investigate how these changed through time and to analyse the rationales behind deploying or expanding large-scale heating infrastructures. The actors and organizations were included to analyse who were the so-called *system builders* (to use Hughes' (1987) original term), the actors driving growth and change, as well as to understand how the organization changed with technological transitions (M. S. Jørgensen et al., 2017). Second, this article focusses on the tools and processes used to implement the infrastructures. Ownership and financing were investigated to understand under which financial conditions large-scale heating infrastructures were built. Following this, the policies, regulation, and legislative responses were also analysed, to investigate how policies, tools, and responses participated together in realizing heating infrastructures (Flanagan et al., 2011). The four

Table 1 Analytical dimensions and main research questions

Analytical dimension	Central questions
Drivers and technology qualities	What were the drivers for expanding large-scale infrastructures?
Ownership and financing	How was ownership structured and how was infrastructure financed?
Actors and coordination	Who were the main actors and organizations?
Policy and governance	Which policy and governance tools were used?

analytical dimensions are presented below in Table 1. These questions are investigated through the different periods covered for each case.

Research design

This paper combines comparative case studies with a longitudinal approach (Bryman, 2016) to analyse the development of the large-scale infrastructures for heat supply over time in the three case countries. The three cases represent successful transitions where energy infrastructures were expanded to high market shares. Cases are well suited to study the development of complex socio-technical systems and provide important examples (Flyvbjerg, 2006) of the actual governance measures, technology qualifications, and organizational changes that engaged with the establishment of these infrastructures. As mentioned above, the countries were selected based on the countries with high shares of DH or NG in their heat supply Bertelsen and Mathiesen 2020). They represent *extreme cases* (Flyvbjerg, 2001) as most countries in the EU-28 have some amounts of energy for heat supply distributed through infrastructures like gas or DH grids, but not to the same extent as the three case countries present in this article. By studying these cases, differences and similarities can be analysed to see under which conditions high market shares were reached. While case studies lack breadth in their numbers, they can provide depth in terms of understanding (Flyvbjerg, 2001).

The main empirical material used is from academic journals and literature describing historical developments in the three cases. The literature search was carried out in the academic search engine Scopus and Google Scholar. Furthermore, literature was found by following the references in already used material (Mason, 2002). Saturation of relevant material was estimated to have been reached when no new material from the references was found.

Analysis of the establishment of heating infrastructures in the United Kingdom, Denmark, and the Netherlands

This section presents the analysis of how the UK, Denmark, and the Netherlands started implementing large-scale infrastructures for heat supply and how they reached high coverage.

Natural gas supply in the United Kingdom

This section analyses the development of the natural gas sector in the UK. The period before 1948 was based on town gas with urban systems covering production and distribution. The nationalization of the UK gas sector in 1948 meant that significant organizational changes were implemented. After the first NG delivery in 1967, a significant transition was carried out, involving the retrofitting of gas appliances, construction of the UK transmission grids, and another sector reorganization. Figure 1 below illustrates the UK residential gas consumption from 1922 to 2000.

Before 1948: gas network beginnings in the United Kingdom

The UK gas supply goes back to the beginning of the nineteenth century, initially manufactured from coal. The Gas Light and Coke Company was granted permission to operate in 1812 by the British Parliament (Williams, 1981), setting out the terms of operation on the gas market. Until 1847, the UK gas supply was characterized by competing firms expanding their networks in the same and most profitable areas and competing for the same customers. Competing

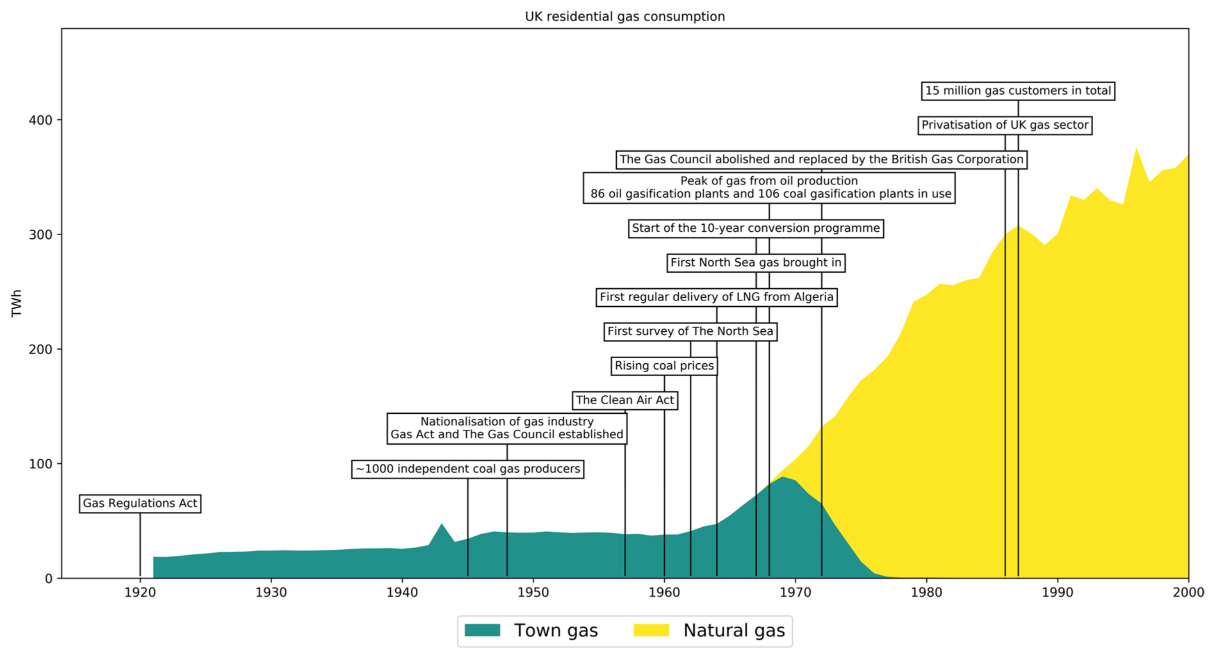

Fig. 1 Development of UK gas supply in households from 1922 to 2000 (Department for Business Energy & Industrial Strategy 2020)

infrastructures in the same areas resulted in supply problems and meant that it was difficult to locate gas leakages and the responsible companies (Millward & Ward, 1993). The UK parliament started to regulate the gas supply in the second half of the nineteenth century to improve conditions for both consumers and suppliers. The regulation included districting where a single supplier was chosen for a specific area; must-supply clauses where consumers who paid the connection fee had a right to be supplied; and a dividend ceiling of 10% (Foreman-Peck & Millward, 1994; Williams, 1981). A price ceiling fixing the price of gas to the price of coal, the closest alternative, was also put in place (Williams, 1981).

Manchester was in 1842 the first city to invest public funds in gas production, and 31% of gas undertakings were municipally owned in 1913 (Williams, 1981). From when the Metropolis Gas Act introduced districting and price regulations, on average, 10 new gas undertakings were established each year until around 1913 (Arapostathis et al., 2013). The Gas Regulations Act of 1920 marked a growing recognition of gas as a premium fuel in the UK (Williams, 1981). It was the beginning of a national governance attempt to standardize the characteristics of gas, by mandating that the calorific value of the town gas in each system be reported, enabling the first small steps to gas trade between systems.

1948–1967: nationalization and reorganization of the British gas industry

Led by the post-war Labour government from 1945–50, the UK began nationalizing several industries including gas, coal, iron and steel, railways, and airways. The gas sector nationalization was realized with the Gas Act of 1948, which implemented a new organization of the sector (Williams, 1981). Twelve Area Boards were responsible for planning the networks, manufacturing and distributing gas, and managing revenue. The Gas Council was responsible for ensuring communication between the Area Boards and with the minister (Foreman-Peck & Millward, 1994; Williams, 1981). The Gas Council was allowed to borrow money from The Treasury to compensate the former owners of the now nationalized gas industry (Williams, 1981). In 1950, two-thirds of the Gas Industry was financed by stocks guaranteed by the Treasury, with one-third coming from the industry itself. From 1961, a return-on-capital investment criterion was put in place, but with lower return criteria than generally used in the private sector (Jenkins, 2004). According to Foreman-Peck and Millward (1994), the nationalized industries operated under three principles outlined in The Nationalization Act: first, to serve a public purpose, second to operate efficiently, and third to break even. Several interpretations of these principles were applied. Serving a public purpose meant that gas grids could be expanded to rural areas, using profits from more profitable sites. Efficient operation was translated into ensuring cost-based billing and pricing and the break-even principle outlined that the gas suppliers could not operate at a loss.

In the 1950s, the future of the gas sector was uncertain with gas sales declining (Jenkins, 2004). Increasing coal prices decreased the profitability of manufacturing gas from coal and electricity started to be competitive in the main uses of gas (Pearson & Arapostathis, 2017). While the coal industry wished to remain the main supplier of feedstock for gas manufacturing and advocated for the Lurgi process using lower-grade coal as a way to decrease gas manufacturing costs, the gas industry itself investigated the potentials of gasification of petroleum and the imports of LNG (Jenkins, 2004). While research was carried out in developing the Lurgi process, the first import of LNG arrived from the USA in 1959, and the year after, in 1960, regular deliveries of LNG arrived from Algeria. The import and use of LNG required establishing gas terminals to receive and process the gas as well as a transmission system to distribute the gas to consumers, which would later prove valuable for NG extraction and transmission (Pearson & Arapostathis, 2017).

Alongside the production changes in the gas sector, the Clean Air Act was approved in 1957 following serious air pollution issues due to coal use for heating. This helped qualify gas as a *smokeless* fuel among oil and other solid fuels, thereby promoting public health by decreasing air pollution. The Clean Air Act introduced spatial planning with the notion of *black areas* where smokeless fuels were mandatory and coal banned (Fouquet, 2012). This prompted the gas sector to expand its market share into central and space heating (Pearson & Arapostathis, 2017).

1967–1977: converting appliances, building transmission grids, and reorganizing actors

The first UK NG fields were discovered in 1965 and the first NG was pumped ashore in 1967 (McHugh, 1983; Williams, 1981). The exploitation of the NG resources in the North Sea hinged on three elements to realize the project. First, the transmission infrastructure had to be expanded to transport the gas from the terminals to consumers. Second, the gas resources prompted end-use changes, in terms of replacing existing gas appliances as well as expanding the gas use, primarily into gas central heating. Third, a new organizational structure was needed for the new type of gas supply.

The UK gas transmission system was expanded from 515 km in 1966 to 5150 km in 1983, with a significant increase from 1970 to 1976 of more than 4000 km (McHugh, 1983; Williams, 1981). The rapid expansion was driven from two sides: the conversion project of household appliances and the North Sea extraction (McHugh, 1983). Committing to the calorific denser NG compared to town gas meant the necessary replacement of existing gas appliances. In total, around 35 to 40 million appliances were replaced from 1967 to 1977, and 14 million customers were visited with an estimated cost of up to £1 billion including sunk costs in obsolete gas manufacturing equipment (Arapostathis et al., 2019; Hanmer & Abram, 2017; Williams, 1981). The conversion program depended on coordinated work between the Treasury and the Ministry of Power who approved the funding, the 12 Area Boards who were responsible for organizing the work in their respective areas, and the many companies, workers, and manufacturers carrying out the retrofits as well as the house owners and citizens who had their gas appliances replaced (Hanmer & Abram, 2017). The Area Boards had the authority to allow access for retrofitters to enter the homes of private citizens if they were not home and carry out the conversion work (Williams, 1981). As shown in Fig. 1, during the conversion project the UK household gas consumption increased from 72 TWh in 1967 to 193 TWh in 1977, largely due to an increase in gas-fires and central heating using gas (Department for Business Energy & Industrial Strategy 2020).

Moving from a gas sector with several systems responsible for their gas manufacturing and

Table 2 Summary of the development of gas infrastructure in the United Kingdom

	Before 1948: manufactured gas	1948–1967: nationalization	After 1967: natural gas discovery, 10-year conversion, and expansion project
Drivers and technology qualities	Economic gains for private businesses Coal supplies Expanding middle class Primarily lighting based	Socio-economic development Serve a public purpose Perform efficiently Clean air—smokeless fuel Changing from lighting to heating	Domestic resource Cheap abundant energy Socio-economic development Primarily heating based
Ownership and financing	Private and municipal undertakings Ownership was specific to the individual system Municipal ownership: Would primarily divert revenue to other public tasks	Public ownership of grids Decentral organization with 12 Area Boards Gas Council coordinates on a national scale Break-even business case for Area Boards	State ownership and management Centralizing ownership, in 1972 nationally governed
Actors and organization	Parliament gives Gas Light and Coke Company permission and terms to operate in 1812 Private businesses Municipalities Consumers	Gas Council Area Boards Ministry of Power Treasury Consumers	British gas The Treasury Area Boards lose influence Extraction companies Appliance manufacturers Consumers getting appliances changed
Policy and governance	Investors were allowed a 10% dividend on their investment Districting specifying supply areas Obligation to supply consumers Price limits	Clean Air Act Gas acts Competition between fuels Nationalization act: public purpose, efficiency, break-even	Gas acts Conversion program: state-led replacement of all household appliances, also without pre-approval from households

distribution, to a sector with a few large supply terminals and a national transmission system entailed organizational changes. In 1939, there were 1019 gas manufacturing plants throughout the UK (Pearson & Arapostathis, 2017). In 1978, there were 5 gas terminals where North Sea gas was delivered and processed. This change is reflected in the authority of the Area Boards and the Gas Council. The Gas Acts of 1960 increased the power of the Gas council with increased borrowing allowances. While the 1960s experienced gradual organizational changes to the Gas Sector, the Gas Act of 1972 reorganized the sector completely (Williams, 1981). The Area Boards were removed and the planning authority was centralized in the new organization British Gas Corporation.

A state governed energy transition for UK natural gas supply

The shift from manufactured gas supply to extracted NG supply was largely state-led, as has also been argued elsewhere (Arapostathis et al., 2019; Pearson & Arapostathis, 2017). The coordination of work and mobilization of resources to build 4.000 km of transmission pipelines and change up to 40 million appliances before 1977 is an example of a large-scale implementation of infrastructure.

Table 2 below summarizes the main parts of the UK transition for the three periods covered. In the pre-nationalized gas sector, manufactured gas was primarily an energy source for lighting and to a lesser degree for heating. Gas was promoted as it was a stable and high-quality energy supply. After nationalization, the gas supply and the sector had to *serve a public purpose*. This meant economic appraisal of gas supply changed from whether the individual connection was feasible, to an overall system focus encouraging overall high connection rates. In 1957, gas was posed to participate in solving air pollution problems, as a *smokeless* fuel. With regulatory tools, The Area Boards could mandate the use of smokeless fuels in areas with significant air pollution.

The actors and organizations reorganized as the sector developed. First, nationalization meant that the sector went from being largely organized around the specific supply systems, to a more aggregated organization with 12 Area Boards and one national Gas Council for coordinating efforts. Later, with the development of the NG system, the organization changed again towards more central steering. Both re-organizations were aligned with the technical configuration of the system at the time. The Area Boards were able to organize the production and distribution of manufactured gas in the respective systems. Each respective system had its supply chains of manufacturing, distribution, and consumption. In the NG system, this changed to a few extraction sites, a vast transmission network supplying consumers. The sector organization changed accordingly, by moving responsibilities from the Area Boards to the Gas Council and later removing them entirely.

Several regulatory tools were used in this transition. In the nineteenth century, when competing infrastructures in the same areas were found to cause problems, districting regulation was used to divide areas between suppliers to avoid competing infrastructures. To mitigate the resulting monopoly situation, must-supply clauses, and profit-ceilings were introduced, although several analyses mention that the profit limitations were not effective (Jenkins, 2004; Williams, 1981). As mentioned above, the Clean Air Act introduced a new form of districting in terms of highly air polluted areas. The geographical location and planning of gas infrastructure remained important. During the conversion program, the Area Boards and their contractors were allowed to enter houses and replace appliances without the house owner present.

Establishment and expansion of district heating in Denmark

The development of DH in Denmark is covered in three periods. The first period before 1960 illustrates the small-scale DH systems and their fragmented development. From 1960 to 1973, the DH sector became more organized and expanded significantly. After the oil crisis in 1973, the DH sector readjusted to oil scarcity and energy security and later utilized new regulatory tools to expand DH coverage. Figure 2 illustrates the Danish DH production and the specific fuels used.

Before 1960: cooperative and municipal ownership of district heating

Transporting warm water for heating and hot water consumption has historically been used in many places, among others in the USA from around 1870 (Bøhm, 1988). The first Danish DH system is often cited to have been from 1903 using heat from waste incineration in the city of Frederiksberg, while in 1945, DH supplied around 3–4% of the total heat demand (Skov & Petersen, 2007). During the economic upswing in the 1950s, DH also started to expand. Larger municipalities and cities developed DH as heat supply for new building developments as well as for areas with high heat density. Smaller communities also began to develop DH, with ownership inspired by the Danish cooperative movement in the agricultural sector. For these systems, the prestige of having a common well-functioning supply system was the main driver (Olsen, 1993). Municipal guaranteed loans and financing were available to invest in this new infrastructure, as municipalities could make a profit on heat sales while guaranteeing the investment.

In 1956, 10 DH plants organized themselves in what would become the Danish DH Association (Skov & Petersen, 2007). The purpose of this new organization was primarily to share technical experiences, to collect and share statistics and knowledge. In 1959, there were around 80 DH systems in Denmark.

1960–1973: expansion of district heating

During the 1960s, DH became more widespread in Denmark. A combination of access to low-interest-rate loans with a municipal guarantee and low oil prices made the business case favourable, although DH was in tight competition with individual oil boilers, similarly benefitting from cheap fuel costs. For consumers, DH was favourable as it provided heat control and did not take up living space as other boilers or furnaces had done (Skov & Petersen, 2007). The beginning of the 1960s saw a high increase in the number of DH companies, with a total of 170 in 1963 and 250 in 1964, increasing the number of companies three-fold since 1959 (Skov & Petersen, 2007). The DH systems were either cooperative, municipal, or in a few instances private, and the expansion was

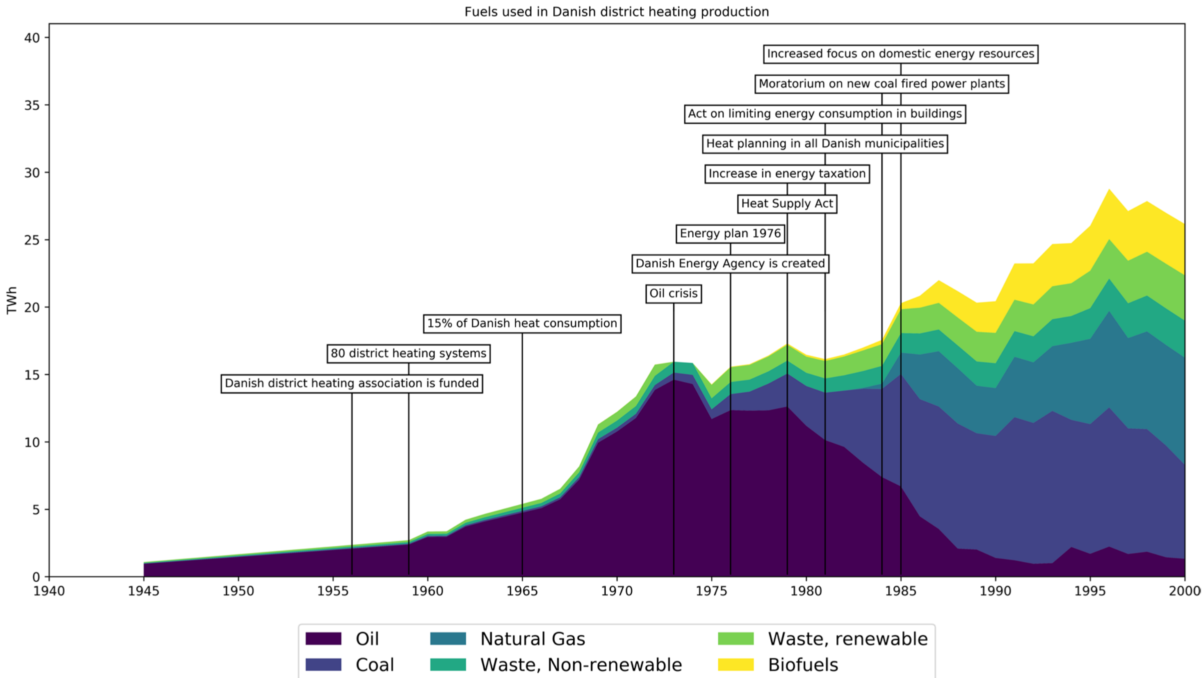

Fig. 2 Development of Danish DH supply and fuels used in production (Danish Energy Agency, 2018; Statistics Denmark, 1964, 2020b)

relying on publicly guaranteed loans for investments into infrastructure. In 1967, the DH Association responded by establishing a new secretariat to begin political lobbying of the Danish politicians (Skov & Petersen, 2007). At that time DH had grown to be a significant heat supply method, supplying 15% of the Danish heat consumption. A favourable financial situation, increased heat quality, and ownership often anchored in the area of supply were central factors that facilitated the development in this period.

After 1973: reconfiguring district heating to oil crisis and energy efficiency

In 1973, OPEC (Organization of the Petroleum Exporting Countries) put oil export restrictions in place as a result of the western alliance with Israel during the war from 6 to 25 October 1973, causing a global oil crisis (Rüdiger, 2014). Just as the DH supply, as shown in Fig. 2 was mostly relying on oil, so was the rest of the Danish society. The Danish response was primarily to decrease energy consumption, having no significant domestic energy resources available (Rüdiger, 2014). Energy efficiency was set to increase both in production and in consumption. The DH producers were mandated to decrease oil consumption by 25%, which primarily had to come from reductions in consumption (Rüdiger, 2019; Skov & Petersen, 2007). Three main approaches were taken to achieve savings in DH: first information campaigns; second price increases to discourage excess consumption; and last the potential for shutting off supply to consumers who used too much energy (Skov & Petersen, 2007). Already in 1975, a 20% reduction of oil consumption in DH was achieved, while the 25% reduction was met in 1980 (Danish Energy Agency, 2018; Statistics Denmark, 1964, 2020b).

While DH largely had been locally governed and developed before 1973, DH began to receive national focus after the oil crisis. In 1976, with the publication of the first national energy plan, the role of DH became central in national strategies for moving away from oil due to the potentials for diversifying fuel supply and exploiting waste heat from power plants (Rüdiger, 2019). The Danish Energy Agency was also founded that year under The Ministry of Trade (Danish Energy Agency, 2016).

In 1979 the Heat Supply Act was approved, to decrease oil for heating and to facilitate a shift to the most socio-economic types of heating (L 206 1979). It also mandated that the state and municipalities did systematic heat planning (L 206 1979, § 4–11). The municipalities were responsible for mapping heat demand, for identifying areas that would be suitable for collective supply (also gas), and for finding the location of industry with high heat demand and high amounts of excess heat. The Ministry of Trade was responsible for the coordination between municipalities and regional authorities, to collect the municipal heat plans and to combine this in a national heat supply strategy.

The municipalities were made responsible for much of the planning and implementation of DH and collective heating. With the Heat Supply Act, they could mandate new buildings to connect to collective heat supply and could ban certain types of heating in specific geographical areas. The municipalities were also tasked with approving new investments in collective heat supply. After the Heat Supply Act was put in place in 1979 and municipalities started doing heat planning in 1981, DH started to expand again, gradually increasing until 1995.

DH companies could only charge necessary costs from fuel, salaries, operation and maintenance, administration, and financing costs after rules set by the Minister of Trade. This is what would be known as the True Cost principle (Danish: Hvile-i-sig-selv), mandating that utilities could not make a profit, but only charge the cost of supply to the customer (Chittum & Østergaard, 2014; Sovacool, 2013). On a national level, a price control authority was established to ensure reasonable consumer prices for heat and gas supply. All utilities had to report their prices to the authority who would make them publicly available.

Initially, the shift away from oil was towards coal in the existing boilers and CHP plants. Simultaneously, there was uncertainty in the Danish energy policy whether nuclear power should have a role in the Danish energy supply. In 1985, it was officially decided that nuclear power would not play a part and instead NG and wind power should be expanded in the electricity supply (Karnøe, 2013; Olsen, 1993). Along with the moratorium on new coal power plants (Danish Energy Agency, 2016), it meant a high increase in decentral, small, gas-fired CHP plants, and meant an increase in DH supply from these sources. In 1992, there were around 350 DH companies in Denmark, with the vast majority supplying heat consumption within the respective municipal borders (Mortensen & Overgaard, 1992).

Individual systems and national regulation for expanding Danish district heating

The Danish DH sector saw two periods of expansion and one with significant internal changes. The first period where supply expanded was from the beginning of the 1960s to the beginning of the oil crisis in 1973. As shown in Fig. 2, DH consumption increased more than fourfold from 3.4 to 16.0 TWh from 1960 to 1973, and during this period, DH established itself as a major source of heat supply gaining the recognition of politicians and municipalities and saw a central role in urban development. Along with the increase in supply, the sector became more organized, expanded its member base, and evolved from only sharing technical experiences to also work with political lobbying. This proved valuable facing the first oil crisis beginning in 1973, which halted the expansion and instigated reconfiguration within the DH sector. Here, the sector had to shift away from its high dependence on oil and was tasked with a 25% oil consumption reduction. This was achieved in 1980, largely by shifting to coal and later towards NG and biomass. Following the period after the oil crisis with mostly internal developments in terms of fuel shifts, the DH sector utilized new regulatory tools which meant the expansion of DH supply from 16.1 TWh in 1981 to 28.8 TWh in 1996.

Table 3 below presents the main elements of the Danish DH development during the period covered. First, the main driver was high quality and affordable heating. For community-owned DH systems, there was a form of prestige in operating a well-functioning DH system, and for municipalities, DH was also a way of generating extra income. These factors changed with the oil crisis where the national government saw DH as a solution to increase energy efficiency and decrease oil dependence. Following the oil crisis, the DH systems were still in charge of governing their development but now with the new policy and planning tools, new energy taxes, and new profit regulation governing the DH sector with the True-Cost principle.

Table 3 Summary of the development of DH in Denmark

	Before 1960: district heating beginnings	1960–1973: establishment	After 1973: oil crisis and requalifying networks
Drivers and technology qualities	High-quality heating Building on the Danish cooperative movement, smaller cities developed DH systems together	Economic growth and expansion of cities Cheap oil Giving more space in houses	Energy efficiency and security of supply Reducing oil dependency Increasing the use of domestic resources
Ownership and financing	Public Cooperative Private (few) Municipal low-interest loans	Public Cooperative Private (few) Municipal low-interest loans	Public Cooperative Private (few) Municipal low-interest loans Financing with True-Cost principle
Actors and organization	Individual systems Danish DH Association facilitates technical knowledge sharing Consumers	Individual systems Danish DH Association begins political lobbying and to further promote knowledge sharing in the sector	Danish state and government Danish Energy Agency (from 1976) and Ministry of Energy (from 1979) Municipalities Danish DH Association increase membership
Policy and governance	Loose	Loose	Heat supply act Districting Energy taxes Potential to shut off the supply

The ownership of the DH system remained stable through the different periods. That means the Danish DH systems largely are owned by their consumers, either through direct consumer ownership or through the municipalities. Access to publicly guaranteed funds for DH networks was an important source of finance throughout the period. The Heat Supply Act introduced the True-Cost principle in 1979, which meant that profit could not be taken from the DH companies but instead had to be given back to the consumers through their heat bill. In practice, this meant that private ownership of Danish DH systems was not attractive for private shareholders seeking profits.

While the sector organization in the UK case changed significantly with the changing supply, the organization of the Danish DH sector remained relatively stable. As DH became established as a heat supply source in the 1960s, the Danish DH Organization also developed to answer new needs for the sector. First, it was primarily technical knowledge sharing, but later, it also became engaged in political lobbying. Second, due to the oil crisis, the Danish state became more involved in energy matters in general and DH in particular. The approach from the state was based on providing opportunities for development and creating awareness among the Danish municipalities, not by taking over the specific control with DH development.

Regulatory tools counted splitting heat supply areas into DH or NG supply, using energy taxation primarily to decrease oil consumption and that new heat supply investments should meet socio-economic criteria and be approved by the municipalities. All municipalities also had to make heat plans for their respective areas, creating knowledge and awareness about DH even in municipalities that did not engage in energy planning at the time.

Natural gas infrastructure in the Netherlands

The Dutch transition from town gas to NG supply is covered in the following and illustrated in Fig. 3. Before 1959, the Dutch gas sector was primarily producing town gas as a by-product of the coal industry. After natural gas discovery in 1959, the gas sector was transformed into accommodating the vast amounts of NG. In 1973, the oil crisis meant

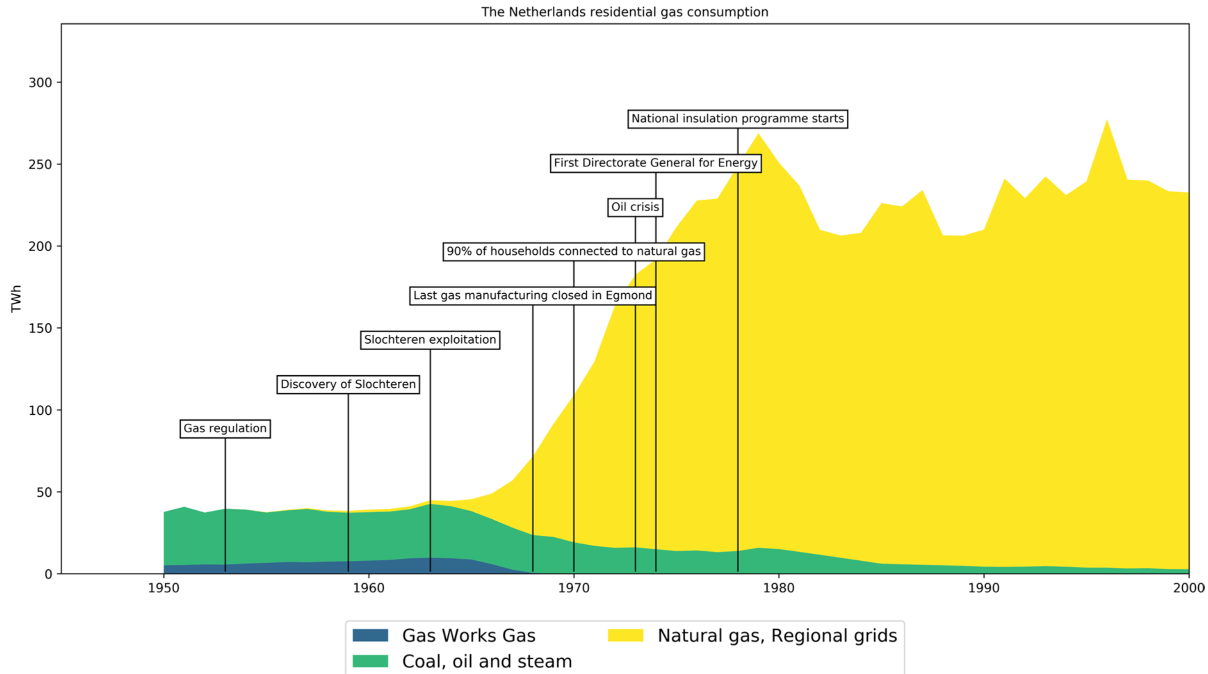

Fig. 3 Development of Dutch gas consumption and other fuels (Government of the Netherlands, 2014; Statistics Netherlands, 2020a, 2020b)

reconfiguring the understanding of NG as an abundant resource to a scarce commodity.

Before 1959: gas beginnings in the Netherlands

Urban gas networks in the Netherlands existed from the beginning of the twentieth century and had been developed by municipalities to use gas produced as a by-product of coke production as a source of complementary income (Correljé & Verbong, 2004). The gas networks in the Netherlands at the end of the 1950s had almost 70% coverage but were fragmented with different suppliers and calorific types (Verbong et al., 2000). They also mostly supplied energy for cooking, where it was considered more practical than both electric and other alternative stovetops (Roberts & Geels, 2019; Wind, 2018). Before the transition to gas, the heating sector in the Netherlands could primarily be characterized by significant under-heating (Van Overbeeke, 2001). Central heating systems were scarce and not included in building codes during the post-war reconstruction, and room heating based on domestic coal and oil stoves common.

Post-war exploration of the Dutch underground focussed on oil, through cooperation between Shell and Esso (later Exxon), who established the joint venture NAM (Nederlandse Aardolie Maatschappij). In 1948, a small gas field had been found, which was used to supply the nearby town of Coevorden (Correljé & Verbong, 2004). While the Dutch state was also interested in NG NAM's primary interest was oil, since gas was not seen as a profitable industry in and of itself (Roberts & Geels, 2019).

1959–1973: natural gas discovery—constructing infrastructure and business models

The trigger for the transition from oil and coal towards NG in heating was the finding of the "super-giant" Slochteren gas field in Groningen in 1959 by NAM, eventually estimated to contain 27 PWh (Correlje & Odell, 2000; Correljé & Verbong, 2004). When the high quantities of gas became clear, it also became clear that the existing policies and governance frameworks were not adequate for this type of resource management (Verbong et al., 2000). Initially, it was still thought nuclear power would materialize

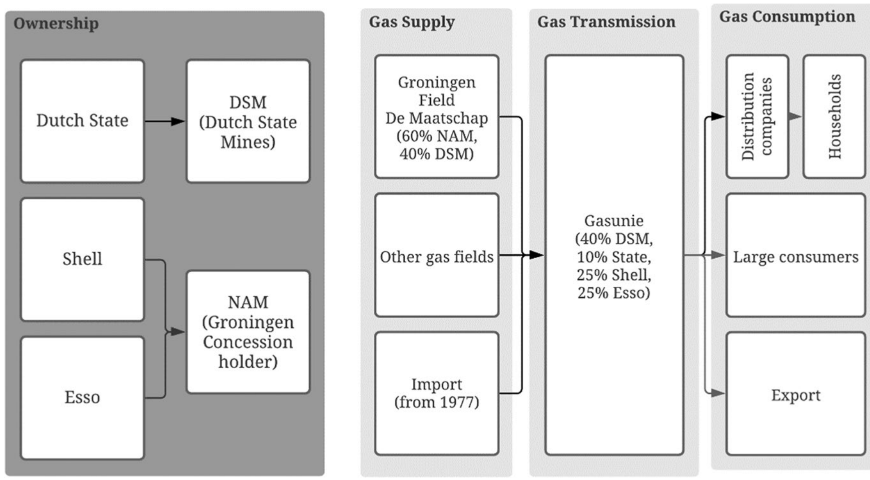

Fig. 4 Representation of the Dutch gas sector for extraction and transmission of gas after the discovery of the Groningen field. Adapted from Correlje and Odell (2000)

as quickly as 10, 20, or 30 years so the objective was to sell gas as widely as possible before the resource would become redundant and thus worthless (Roberts & Geels, 2019; Weijermars & Luthi, 2011).

To exploit the vast NG resources the Dutch gas sector faced a significant reorganization, infrastructural, and technical developments as well as a new business model and pricing scheme for selling gas (Correljé & Verbong, 2004). Dutch State Mines (DSM) were chosen to represent the Dutch state. DSM had experience in gas manufacturing from coal and was a large organization experienced in negotiations, and perhaps most importantly, including DSM meant they could stay relevant in the new gas regime that would eventually make coal mining obsolete (Correljé & Verbong, 2004).

The new organization of the sector was presented 3 years after the discovery of the gas field (Correlje & Odell, 2000). The concession was given to NAM and two new public–private companies were formed, presented in Fig. 4. De Maatschap was formed between NAM (60% share) and DSM (40% share) to be in charge of gas extraction. Gasunie was founded by Esso and Shell directly (25% share each), DSM (40% share), and the State (10% share), being responsible for the purchase, transport, and sale of gas (Roberts & Geels, 2019; Verbong & Schippers, 2000). The Dutch State gathered 70% of the profits through direct ownership, indirectly through DSM, through a 10% royalty, and through the companies' taxable profits (Verbong & Schippers, 2000).

Esso proposed a business model that focussed on the household market comprised of many small consumers, to ensure offtake and turnover (Correljé et al., 2003). To ensure a large uptake, a substitution price model was proposed through negotiations with Esso, Shell DSM, and the Dutch State. The idea of the substitution price model was that gas used for lighting would be priced just below electricity and gas used for heating would be priced just below the price of oil. Private households would get the lowest price per cubic metre gas by using gas for heating, thereby ensuring high sales volumes (Correljé & Verbong, 2004). Choosing the substitution price model entailed a large-scale deployment of NG to the Dutch households, which relied on developing a large-scale national transmission network covering the Netherlands.

The newly formed Gasunie was tasked with expanding the national transmission system to connect the independent gas systems. Much of the initial profits from the gas export and expansion were redirected towards infrastructure and enabling market growth, by using profits from initial sales in dense areas to continue expanding networks in more sparsely populated sites (Correljé & Verbong, 2004; Correljé et al., 2003). The high ambitions for a transport grid connecting Groningen with the rest of the country meant constructing 1.600 km of transmission pipelines in less than 5 years and doubling the total length of gas networks to 5.000 km (Correljé & Verbong, 2004). Distribution grids were often bought out and expanded (Roberts & Geels, 2019). These combined interventions resulted in a rapidly expanding network, switchover of equipment, and a remarkable increase in gas usage, as gas started to be used for heating.

In 1963, the Dutch gas usage in households was 45 TWh, which increased to 182 TWh in 1973 and later reaching 253 TWh in 1979 (Government of the Netherlands, 2014; Statistics Netherlands, 2020a, 2020b). This high increase in gas usage is shown in Fig. 4. To develop a domestic heating market, massive campaigns were developed by Gasunie. This initially started at fairs, but quickly developed into newspaper, radio, and television campaigns (Wind, 2018). The enthusiasm was so encouraged that by the time the network was expanding, there would be literal "connection parties" organized for villages, including balloons filled with NG (Roberts & Geels, 2019; Verbong & Schippers, 2000). Ease, cleanliness, safety, and reliability were a key part of this message, both in pre-empting the need to stock oil or coal on the premises and also with the introduction of thermostats with central heating that rendered manual controlling irrelevant (Roberts & Geels, 2019; Verbong & Schippers, 2000).

After 1973: adapting natural gas supply to scarcity

The oil crisis of 1973 also hit the Netherlands with increased oil prices and the prospect of potential oil scarcity (Correljé et al., 2003). For the gas sector, the perception of an abundant energy source changed to a valuable commodity that needed to be used with caution (Correlje & Odell, 2000). As a response, the first Dutch white paper on energy was published in 1974, outlining energy savings and diversification as the energy policy approach (Correljé et al., 2003). The white paper described that gas was only to be used in places where it added value compared to either coal or fuel oil. This included households where no restrictions on gas use or conversions were put in place (Correljé et al., 2003), resulting in a still increasing gas consumption until 1979.

While the oil prices quickly increased due to the oil crisis, the gas price using the substitution principle did not follow as abruptly. The gas price could only increase after a time lag and with a reduced percentage (Correljé et al., 2003). Rising prices and responding to a call for national energy conservation were the main incentives for consumers to start insulating their houses, to buy more efficient boilers, and halt the growth in energy demand.

Natural gas in the Netherlands: public–private partnerships for gas supply

The Netherlands achieved high coverage of NG infrastructure with a new organization, a new business model, and by using profit-sharing to expand the networks. Rolling out NG meant that a new transmission grid had to be built, but much of the already existing distribution grids used for town gas could be repurposed. Cooperation between the Dutch state, publicly owned companies such as DSM and the private companies Shell and Esso and their joint venture NAM, was successful in a rapid transition to NG supply. While extraction primarily relied on NAM using the expertise of Shell and Esso, building the grids and ensuring that a functioning transmission and distribution system was available was primarily a task for the Dutch state, municipalities, and Gasunie.

The Dutch transition through three periods is summarized below in Table 4. The primary driver behind the roll-out was the significant volume of the discovered resource. It was cheap, easy to extract, and of high quality. It gave the under-heated Dutch households access to an energy source that made coal deliveries redundant and the heating was easier to control at a slightly lower price. The Dutch transition to NG supply was largely driven by public–private cooperation, utilizing an abundant and cheap resource that later proved valuable in maintaining domestic energy security. The transition used existing public organizations and infrastructure and with profit-sharing between areas of different profitabilities, a high coverage of gas infrastructure was achieved. An important aspect of achieving high coverage of NG in the Netherlands was the pricing policy of gas. By aiming at a high coverage among small consumers, a high volume was achieved. As the alternative heating source at the time was of poor quality, NG had two advantages. First, the price was set just below that of the alternative, and second, it provided a higher quality supply. This relied on the specific physical properties of the Groningen field, where extraction was cheap.

While the partnership responsible for gas extraction of Groningen, De Maatschap, had private majority ownership, De Gasunie had equal private and public ownership. The extraction of NG was controlled by Shell and Esso who had previous experience in energy extraction, while building the transmission grids, as well as the distribution and sales, was managed by public companies. The Dutch

Table 4 Summary of the development of gas infrastructure in the Netherlands

	Before 1959: gas network beginnings	1959–1973: transition to natural gas	After 1973: from abundance to scarcity
Drivers and technology qualities	Excess from the coal industry Easier for cooking Different types of gas	Domestic and cheap energy source High quality Abundant fuel Easy, clean, and secure for consumers	The oil crisis and increasing energy prices Energy scarcity NG an important domestic resource Easy, clean, and secure for consumers
Ownership and financing	Local system ownership—each system was owned individually either by municipalities or private businesses	Gasunie owns and develops national grids Gasunie invests in distribution infrastructure Public–private partnerships for extraction Profit-sharing from dense to rural areas	Gasunie owns and develops national grids Gasunie invests in distribution infrastructure Public–private partnerships for extraction Profit-sharing from dense to rural areas
Actors and organization	Municipalities Coal sector SGB	Dutch state DSM, the state coal mines NAM, 50% Esso, and 50% Shell Gasunie (40% DSM, 10% state, and 50% NAM) De Maatschap (60% NAM and 40% DSM)	Dutch state DSM, the state coal mines NAM, 50% Esso, and 50% Shell Gasunie—distribution and gas sales (40% DSM, 10% state, and 50% Nam) De Maatschap (60% NAM and 40% DSM)
Policy and governance	Loose	Profit-sharing between areas Profit and risk-sharing between companies and the state	Energy-saving measures Insulation programs Only use natural gas where most important

NG supply relied on the coordination of many actors and organizations. Some already existing public organizations had to be enrolled to support the new NG system. DSM, the Dutch coal-state mines, when chosen, absorbed much of the pre-existing gas sector actors under one umbrella and allowed for key national actors to participate in a shift away from declining dependence and production of Dutch coal towards a newly ascendant resource. By using their knowledge in corporate negotiations, gas manufacturing, and energy sales and exports, they were included in the new NG regime and supported the shift to the new energy supply. The profit-sharing mechanism between densely and sparsely populated areas made high connection rates possible and allowed for heavy subsidies towards equipment changeover. The high profits from the cheap gas source of Groningen also made it possible to acquire obsolete assets in gas manufacturing plants, to invest in existing grid infrastructures, and facilitated the development of a national gas grid.

Discussion: similarities across three transitions to large-scale heating infrastructures

The analysis in this paper focussed on four main elements to investigate the transition towards large-scale infrastructures for heat supply. These were (1) *drivers and technological qualities*, (2) *ownership and financing*, (3) *actors and organizations*, and (4) *policy and governance.* Important aspects of implementing infrastructures were found in all categories and will be summarized below to inform about future infrastructural development.

First, the ability to solve societal problems was an important driver for establishing infrastructures. None of the grid infrastructures started as carefully planned transitions but were built upon small-scale fragmented infrastructural systems. In Denmark, the UK, and the Netherlands, global events changed the energy discourse, and these were important in the reframing of infrastructures and their societal problem-solving abilities. In the UK, these events were first the nationalization of the gas sector and later the discovery of vast NG resources. The Netherlands first discovered NG and later reconfigured the gas resource and supply to counter the oil crisis of the 1970s. In Denmark, it was also the oil crisis that reconfigured the DH sector to reach high market shares. While the grid infrastructures remained in place, their meaning and purpose changed through time to meet new societal challenges. Following Miller and Rose (2008), the framing and problem-solving abilities of the infrastructures changed as new challenges emerged, and through this transition, the infrastructures remained relevant. The question of whether climate change constitutes a crisis sufficient for sparking similar large-scale changes thus arises. The scale and potentially harmful consequences of climate change (Steffen et al., 2018) are one of society's great contemporary challenges. It is less clear how this crisis translates into concrete action as actors attempt to mitigate the harmful consequences based on their own particular situations. This is where the importance of concerted action from national governments and international authorities arises, in creating the necessary conditions and environments for municipalities, utilities, and investors to engage with the threats from climate change in a coordinated manner.

Second, public ownership of the grids and distribution infrastructures was important in all cases. Expanding the grid infrastructures to such high market shares relied on profit-sharing mechanisms between highly and less profitable areas, where surplus profits from dense areas could be used to expand infrastructure in less dense and conversely less profitable areas seen from a business economic perspective. While public ownership of the grids was central in all three cases, both public and private actors were engaged in developing the NG sectors. In the UK, the private gas undertakings before nationalization relied on permissions to operate and benefit from districting regulation and the gas act, while in the Netherlands public–private partnerships drove the development.

It highlights that such infrastructures were not realized only through competition, liberalization, and market forces. Instead, they were built through collective efforts, long-term planning, and concerted action by actors. While all cases are different and depend upon the specific conditions they exist within, the three case studies presented in this paper highlight that an active role of public authorities in some capacity is likely necessary when establishing transmission and distribution infrastructures to enable the low-carbon transition.

Third, many public and private actors were involved with developing the infrastructures. It was important to maintain coordination and communication between the different actors, whether being different public organizations at municipal, regional, or national levels or between public and private actors. Incumbents and established organizations proved important in moving the infrastructural developments forward, as also argued by Turnheim and Sovacool (2020). Both the UK and the Netherlands benefitted from already existing organizations and actors responsible for distributing gas to consumers when NG was discovered. When the oil crisis hit Denmark, it was possible to use the already existing DH systems and organizations to further promote coverage. Instead of new emerging actors, it proved important to reconfigure existing ones and align their objectives with new societal purposes. This was successfully achieved in the Netherlands with the involvement of DSM and in Denmark where municipal heat planning was made mandatory. Both the Dutch DSM and the Danish municipalities became involved in developing the emerging infrastructures.

When establishing new large-scale infrastructures for energy-efficient and low-carbon energy supply, it is important to consider the conditions that actors operate within. It is a central role for national governments to make sure conditions that support the envisioned transitions are in place, where actors responsible for the specific technology implementation, investments, and maintenance can operate within. Countries with existing utilities and actors responsible for energy supply might utilize these if they can adopt to new roles to support the transition. On the other hand, such powerful incumbent actors can also prove to be major barriers. Countries without such infrastructures and actors face a different problem. With no existing actors with knowledge, expertise, or capacity to act, there is lacking responsible parties to carry out the transition. At the same time, in such situations, new large-scale infrastructures do not have to compete with already established energy infrastructures. Fourth, different policies were used to solve specific challenges and used to develop energy infrastructures. Some examples include the *Clean Air Act* in the UK promoting gas as improving air quality, and the Danish *Heat Supply Act* that stipulated DH supply areas. Both the UK and Denmark relied on spatial policies and districting to specify which fuel types could be used in which areas. In the Netherlands, the government largely relied on identifying the right business models that would ensure high coverage and a suitable return on investment to keep developing the grids. It shows the importance of effective policy and governance regimes that enable actors to carry out the planning, investments, and implementations of new technologies. Such implementation does not happen in a vacuum but in existing contexts where stakeholders act based on the specific situations.

The cases highlight that the interaction between these four aspects is important and that they together participated in the successful development of large-scale infrastructures.

Implications for contemporary energy transitions

Energy efficiency improvements can be found across the energy system and large-scale infrastructures can play an important role in realizing these potentials. Energy efficiency first is an important principle in EU energy policy and governance (European Parliament, 2018a). Establishing large-scale district heating grids allows exploiting otherwise lost energy for heating purposes and should therefore be assessed as a part of any energy efficiency strategy. It is important to see the energy efficiency first principle from an energy systems perspective to identify savings across different energy sectors and in different parts of the supply chain. Energy savings through renovation, increased insulation, or demand-side management should systematically be compared with energy-efficient investments in the supply, distribution, and transmission parts of the energy system (Hansen et al., 2016). The Danish and Dutch cases show how large-scale infrastructures can be deployed as energy efficiency measures.

Significant policy and governance work is already being done at EU level to adopt district heating systems in European heat consumption to promote energy-efficient and low-carbon supply. Examples include the Energy Efficiency Directive (EED) (European Parliament, 2018a) and the Renewable Energy Directive (RED) (European Parliament, 2018b). The Governance of the Energy Union and Climate Action (European Parliament, 2018c) outlines a common approach for how to transition European energy consumption towards efficient and low-carbon supply by mandating that member states make National Energy and Climate Plans (NECPs). The NECPs are individual assessments of the specific member states' goals, plans, and potentials within decarbonization, energy efficiency, energy security, energy markets, and research and innovation. Being similar to the Danish approach where the Heat Act mandated that municipalities made Heat Plans, now member states are tasked with making comprehensive plans from energy efficiency and decarbonization perspective. The NECP methodology and member states' approaches for enabling the construction of DH grids should not only consider the large-scale infrastructures from a technical point of view, but also integrate policy, ownership, regulatory, and stakeholder aspects into their governance attempts to promote the large-scale infrastructures. As the three case studies in this article have shown, it is important to consider the societal drivers, actors, ownership, regulation, policy, and financing when establishing large-scale infrastructures for heat supply.

Conclusions

Significant work was involved in accomplishing the implementation of high coverage of the large-scale infrastructures for heat supply. All three countries saw large public, long-term investments into public grids for energy transmission. Both the speed and extent of the transitions were significant. In the UK, it meant the replacement of 40 million appliances, building 4.000 km of transmission grids, and increasing residential gas consumption from 72 to 193 TWh before 1978. The Netherlands also managed to replace appliances, develop a national grid, and increase residential gas consumption by a factor of four during 10 years. In Denmark, DH increased fourfold from 1960 to 1973, and as part of the energy efficiency response to the oil crisis, Denmark reduced oil consumption in DH by 20% in 3 years and realized the target of a 25% reduction in 1980. The Danish case shows that implementation of large-scale infrastructures does not need to be driven by discovering large external fuel resources, such as natural gas. Rather, the three transitions of implementing large-scale infrastructures for heat supply were the results of coordinated work between national governments, municipalities, consumers, and private businesses, utilizing novel business models and regulatory tools such as energy taxation, spatial planning, and categorization of which energy types that should be promoted and which should be phased out.

Different types of ownership and state involvement were used in three cases. The UK nationalized the gas sector and organized it with Area Boards responsible for production and distribution in their respective areas with the Gas Council managing coordination. After the discovery of NG, the UK gas sector became more centralized, both in terms of production and organization. In the Netherlands, cooperation between public and private actors managed the roll-out of NG systems, where private companies had the main responsibility for extraction and public organizations participated in transmission and distribution of gas. In Denmark, the DH systems were mostly owned either by the municipalities or the consumers themselves. The Danish DH systems differ from the Dutch and UK NG systems in the sense that they maintained ownership over their systems, unlike the gas systems that were largely merged into one national transmission system after NG discovery. While the ownership models differ through the cases, a degree of public ownership of the grid infrastructures is present in all the cases and highlights the importance of being able to share profit from one area of development with another to reach high coverage.

All three countries managed to utilize the existing technical infrastructure and align the agendas of existing organizations to expand the infrastructures. Examples include how the Dutch State Mines, DSM, were included in both extraction, distribution, and sales of NG, and how the nationalized UK gas industry was quickly reorganized to support a centralized NG approach instead of local gas manufacturing. One important finding in this paper is thus the importance of incumbent organizations and already existing infrastructure in realizing the significant roll-out of the large-scale infrastructures for heating. Three different models for expanding the grid infrastructures were used and country-specific business models, regulation, and governance formed part of the transitions. This highlights that socio-technical transitions must adapt to the specific circumstances they are developing in.

This paper has also highlighted that while large-scale infrastructures have long lifetimes and are resistant to material changes, their meaning and societal purpose have changed more flexibly through time. Especially the oil crises in the 1970s changed the understanding of large-scale infrastructures. In Denmark, the role of DH changed from a local high-quality heat supply to a national strategy of increasing energy efficiency and decreasing oil dependence. In the Netherlands, gas changed from an abundant resource to a scarce energy source to be used in the most important places. The UK gas supply took on a number of different meanings including gas as a *smokeless fuel* and *serving a public purpose*. In this sense, the same infrastructures were repositioned as solutions to the newly emerging problems as societal challenges shifted. While they are materially obdurate with long lifetimes and significant fixed investment costs, their purpose, societal understanding, and relevance changed significantly in the three cases.

Large-scale infrastructures for heat supply in the UK, Denmark, and the Netherlands were achieved through a combination of first, aligning the heat supply infrastructures as solutions to societal problems, second, using ownership and financing models that allowed widespread development and coverage of grid infrastructures, third, ensuring coordination between and involvement of several important actors and organizations both private and at different levels of government, and fourth, deploying governance and regulatory tools to aid in the establishment and coverage of large-scale heat supply infrastructures. These four aspects could potentially aid in novel developments of large-scale grid infrastructures to address current societal challenges and issues, in the form of district heating for a decarbonized heat supply.

Acknowledgements We thank the Horizon 2020 Hotmaps project (Grant Agreement number 723677) for partial funding of this work. We also thank the anonymous reviewers for their constructive feedback and comments.

Author contribution Conceptualization: Nis Bertelsen, Brian Vad Mathiesen; methodology: Nis Bertelsen; formal analysis: Nis Bertelsen; data curation: Nis Bertelsen, Susana Paardekooper; writing—original draft preparation: Nis Bertelsen, Susana Paardekooper; writing—review and editing: Nis Bertelsen, Susana Paardekooper, Brian Vad Mathiesen; visualization: Nis Bertelsen; funding acquisition: Brian Vad Mathiesen; supervision: Brian Vad Mathiesen. All authors have read and agreed to the published version of the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

Disclaimer The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Gaps and ambitions in the goals and policies of the EU-27 National Energy and Climate Plans

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Abstract

EU energy and climate governance relies on the individual member states planning for the development of their energy supply to meet the EU and Paris Agreement targets. The National Energy and Climate Plans outline the paths towards fulfilling the EU energy and climate targets in 2030, importantly the newly revised goal of a 55% reduction of greenhouse gas emissions, 32% renewable energy and a 32.5% improvement in energy efficiency. This article reviews energy and climate targets as well as the policies and measures deployed to reach them. There is a high focus on decarbonizing electricity supply and electrification of other sectors, but targets for heating & cooling and transport lack ambition. National energy efficiency goals entail a significant primary energy reduction but not a large reduction of final energy and end-use. Natural gas and fossil fuels still dominate energy security measures and development. For the next round of NECPs there is a need to increase ambitions to meet new climate targets and to find ways to maintain energy security without the need of fossil fuels.

Highlights

- The 27 MS have ambitious targets for renewable energy in electricity supply.
- The heating & cooling and the transport sector have relatively low renewable energy targets.
- Most policies and measures in the NECPs focus on electrification and potentially miss important sector coupling potentials.
- The energy security dimension is dominated by fossil fuel and natural gas plans and pose a challenge for a full decarbonisation of energy supply.

1 Introduction

The European Union (EU) is increasingly committing to decrease greenhouse gas emissions to limit climate change in accordance with the Paris Agreement (European Commission 2019a; European Commision 2019). While the EU has adopted ambitious climate and decarbonisation policies, it lacks the mandate to interfere in national energy configuration and policy mixes of the Member States (MS's) (Ringel and Knodt 2018). Instead of having binding national targets concerning renewable energy and energy efficiency, a national reporting scheme was set in place under the current Governance Regulation (European Parliament 2018c). One mandatory target is to reach a 30% reduction in greenhouse gas (GHG) emissions in the Non-ETS sectors, including transport, buildings, agriculture, non-ETS industry and waste (European Parliament 2018d). The Member States are tasked with outlining national energy and climate targets for 2030 and policies for how to achieve these in National Energy and Climate Plans (NECP's). The NECP's use a common template to cover the five topics of the Energy Union (European Commission 2015): *Decarbonisation, Energy Efficiency, Security of Energy Supply, Internal Energy Market, Research, Innovation and Competitiveness*.

Since the beginning of the new millennium, The European Council has worked on developing a common European energy policy, balancing national interests and sovereignty with concerted action and cooperation (Thaler and Pakalkaite 2021). Since the adoption of the Lisbon Treaty, EU energy governance and policy has experienced what Szulecki et al. (2016) call a ‘hesitant supra-national turn’, giving more agency to the European Commission in matters of energy policy. The NECP system has evolved from past EU regulation outlining the need for MS’s to make action plans for energy efficiency and renewable energy. Clean Energy for All Europeans, also known as the “Winter Package” from 2016 (European Commission 2019b) outlined overall energy efficiency and decarbonisation goals for the EU block, but lacks any binding national targets (Ringel and Knodt 2018). The most recent addition to the EU energy policy repertoire, the European Green Deal (European Commission 2019c), aims at net-zero greenhouse gas emissions in 2050, which is proposed to become binding with the European Climate Law (European Commission 2020a).

Recently a 55% GHG emission reduction target has been adopted (European Commission 2020b) which will further tighten the need for more renewable energy, energy efficiency and integration technologies such as energy storage, smart electricity and energy infrastructures. Currently the EU targets for energy efficiency and low-carbon energy supply are:

- 55% reduction in greenhouse gas (GHG) emissions in 2030 compared to 1990. The NECP plans are based on the old target of 40% reduction (European Commission 2020b).
- 30% GHG emission reduction to be achieved by the non EU-ETS sectors (European Parliament 2018d).
- 32% renewable energy in 2030 (European Parliament 2018b).
- 32.5% energy efficiency in 2030 relative to a business as usual scenario (European Parliament 2018a).
- Long term strategy of achieving carbon neutrality in 2050.

While the EU targets are ambitious, the efforts needed to fulfil the Paris Agreement (UNFCCC 2016) still present a vast challenge. The International Energy Agency show that to reach net-zero emission energy supply in 2050, a drastic reduction in fossil fuels and no new exploration of oil or gas fields is necessary (IEA 2021). Outside of public policy and governmental plans there exists several techno-economic studies that outline how energy supply could be decarbonised. The Heat Roadmap Europe (HRE) studies have investigated how heat supply can be decarbonized in the context of a low-carbon energy system, and district heating, CHP, heat pumps and energy efficiency are all important technologies and approaches in reaching this goal (Persson, Möller, and Werner 2014; David et al. 2017; Möller et al. 2019). More specifically, the HRE studies point out that 50% of the EU heat consumption could be cost-effectively supplied with district heating (Paardekooper et al. 2018). Such an approach also relies on a high increase in electricity generation from wind, photovoltaics as well as CHP plants when intermittent generation is unavailable (Connolly, Mathiesen, and Lund 2015; Thellufsen et al. 2020; R. Lund and Mathiesen 2015). Transport and mobility could be supplied by a significant electrification while limited biomass resources green fuel production could be used in heavy transport, aviation, industry of flexible power plants (Korberg et al. 2021; Mortensen et al. 2020).

The NECP’s outline the energy and climate goals and measures of the EU-27 MS’s going towards 2030, and can therefore provide important information on how the MS’s plan to transition their energy supply. 2030 is outlined in the Clean Energy for all Europeans package (European Commission 2019b) as an important target moving towards a climate neutral energy supply in 2050. This study reviews the targets and measures set out by the MS’s in their NECPs and analyse which solutions form part of the MS’s measures for decarbonizing energy and energy efficiency. The paper proceeds in the following way. First, the methods are presented, explaining how the data was collected and analysed. Second, the results are presented, going through targets for sectors in the energy systems as well as the policies and measures that the EU-27 MS seek to deploy. Last, a discussion and conclusion summarize the findings and discuss their implications.

2 Methods and research approach

The initial dataset consist of the NECP’s from 27 countries, a total of 30 documents as Poland has handed in 3 and Belgium 2 (European Commission 2021b). The dataset consists of 7408 pages with an average length of 247 pages per document. While the NECPs contain detailed information about the specific plans of each MS, making an overview of the 27 MS's efforts required summarizing the data in a useful way.

As mentioned above, the NECPs all follow the same template. The plans are structured as follows. Section A contains an overview of the plan, a chapter on *National Objectives and Targets* and a chapter on *Policies and Measures.* Section B contains information on the *Analytical Basis*, current situation and projections as well as impact assessments of the planned policies and measures. For the purpose of this paper, only Section A contain information regarding energy and climate targets and the related policies and measures was reviewed. Both the *National Objectives and Targets* and *Policies and Measures* chapter are structured under the five key dimensions *Decarbonisation, Energy Efficiency, Security of Energy Supply, Internal Energy Market, Research, Innovation and Competitiveness,* which proved useful for organizing the data collection.

2.1 Data collection

The data collection was done by manually going through the NECPs, registering all targets, goals, policies and measures in a spreadsheet with predefines categories. Each category had a number of attributes, where a predefined list was made, but which was gradually adjusted throughout the data collection process to make a better fit with the data.

The categories and their related attributes are presented below in Table 2.1. For each target, goal, measure or policy, the information summarised in the table was recorded. Generally, the targets in the *National Objectives and Targets* chapters were quantitative targets while the content in the *Policies and Measures* chapters were of a more descriptive, qualitative nature. For example, a target in the *National Objectives and Targets* chapters might specify that a certain country aims at having 50% renewable energy in their electricity supply by 2030. A policy in the *Policies and Measures* chapters could then describe that wind power production will be promoted by a new financial support system.

A full list of the categories and their attributes are provided in the Appendix. After the data collection, some data cleaning and management was necessary in order to organise the data for analysis. This included merging some attributes either due to misspellings during the registration or due to very similar content. Energy units were also all converted to GWh.

Table 2.1 Categories and attributes used to classify the data

Categories	Content	Example of attribute	Relevant NECP Chapter
Chapter	Chapter of the NECP	National Targets And Objectives	Both
Dimension	Dimension of the NECP	Decarbonisation	Both
Sector	What energy system sector is the measure related to?	Electricity	Both
Unit	What unit is the measure expressed in?	GWh / Percentage	Objectives and Targets
Targets	What kind of target is it?	Share of renewable energy	Objectives and Targets
Type	How is the target measured?	Primary energy supply / Final energy consumption	Objectives and Targets
Range	Is the target specified in a range?	Low / High	Objectives and Targets
Energy system part	What part of the energy system is the measure addressing?	Energy conversion / distribution	Policies and Measures

Technology	What type of technology / solution is the measure addressing?	District heating / Energy efficiency	Policies and Measures
Type of measure	What kind of measure is it?	Financial & Fiscal / Information & Training	Policies and Measures
Aim or mandatory	Is the measure mandatory or an aim?	Aim / mandatory	Policies and Measures
Short text	A short description of the measures	Increase level of electrification of the railways from 73% to 85% by 2030	Policies and Measures

Measures which does not directly relate to energy production, consumption or energy systems in general are not included in this analysis. For example, this means that policies and measures aimed at reducing waste or land use changes in the agricultural sector are not counted. Measures where waste or biomass from agriculture is used for energy production are included in this analysis. Therefore the results does not cover all measures in the NECPs but only the ones that are energy related.

The *sector, technology* and *type of measure* categories have central explanatory role in the following analysis and also required a certain interpretation during the data collection phase. Therefore they are explained in greater depth here. All the individual sectors, technologies and types of measures are listed in the appendix.

2.1.1 Sectors

Some of the defined sectors overlap or contain several of the other sectors. The *Societal* sector category contains measures which can apply to all the other sectors, while the *energy sector* category primarily contains measures which combines efforts on the *Electricity, Heating & Cooling* and *Fuels* sector.

2.1.2 Technologies

Measures which address specific technologies are recorded with this specific technology focus, for example wind or heat pumps. Measures which address types of technologies or several technologies together where recorded under a more general category. Measures which does not have a specific technology or technological category in focus is labelled as *Broad Technological Focus.*

2.1.3 Type of measure

The type of measures is a broad range from financial, information to regulatory aspects. The *general* measure category covers broad measures that do not describe in detail the specific governance tools used to achieve that policy.

2.2 Data analysis

The analysis of the recorded data was split into two main parts. First, the mainly quantitative goals and targets from the *Objectives and Targets* chapter are analyzed, followed by the more qualitative data from the *Policies and Measures* chapter.

2.2.1 Objectives and Targets – quantitative data

For the *Objectives and Targets* dataset, the decarbonisation goals of the MS's were identified within the sectors of *Electricity, Heating & Cooling, Transport* as well as the *Overall* decarbonisation targets. Some reporting differences was identified between the countries. For example, some MS report a share of renewable energy for the overall society while some countries only report for the energy sector or use different reference years. For GHG emission reduction targets, the EU targets of non-ETS sectors is also reported. This is due to the consistency of this target across the different MS's. Several MS's have more ambitious GHG emission reduction targets than these, that also include decarbonisation of the ETS sector.

For the *Energy Efficiency* target, the process was more complicated. Energy efficiency targets usually consist of a reduction target, type of reduction, a target year, a starting year and a baseline year. An energy efficiency goal can for example be 30% reduction of primary energy supply in 2030, from 2020 compared to a baseline in 2010. The NECP methodology does not specify common baselines, starting years or if energy efficiency targets should relate to primary or final energy, which results in energy efficiency targets that are difficult to directly compare between countries. To be able to compare the planned energy efficiency improvement across MS's, the projected absolute energy consumption targets were collected for primary and final energy. These are all reported for 2030. Then a baseline of energy consumption was established by using data from Eurostat on total and final energy supply (Eurostat 2021a, 2021c). The baseline for final and total energy consumption was calculated as an average between 2015 and 2019 to avoid any yearly fluctuations. This allowed for comparing the MS's targets in 2030 with the actual energy consumption between 2015 to 2019. This calculation highlights and compares the MS's planned energy consumption reductions, but does not directly compare to the EU 32.5% energy efficiency target.

The energy targets were weighted with final energy consumption data from the respective sectors to calculate the average targeted share of renewable energy across the 27 MS's. Total final energy consumption, final electricity consumption (Eurostat 2021a) and final energy consumption for transport (Eurostat 2021b) was used to weigh the targets for the share of renewable energy in the overall energy supply, electricity and transport. Data for residential heat consumption and district heating consumption from Bertelsen and Mathiesen (2020) was used to weigh the renewable energy targets in heating & cooling and district heating energy supply.

2.2.2 Policies and measures – qualitative data

The *Policies and Measures* chapter is primarily analyzed based on a count of the different types of measures in order to estimate how many measures target a specific sector or technology. A significant limitation to this approach is that simply more measures are not equal to effective policies. Still, a count of measures across the EU-27 MS's still indicate how much focus certain sectors or technologies receive in the NECP's.

To further add to an understanding of the focus and content of the recorded measures, a TF-IDF (Term Frequency-Inverse Document Frequency) analysis was carried out on text samples collected for each measure. It is a method used in automated text analysis, natural language processing (NLP) and as used here, for feature extraction from text (Patki and Khot 2017). It is a measure that attempts to identify important words in a sentence compared to the whole collection of sentences.

First, the sentences were stemmed and stop-words removed. Stemming reduces words to their stems, so that words such as *decarbonized, decarbonisation, decarbonizing* all are reduced to *decarbon.* Stop-words are commonly used words that do not contain meaning such as *the, a, an, in.* Stop-words were removed and words stemmed using the NLTK python package (NLTK 2021).

For the calculation of a TF-IDF score, the Scikit-learn package (Pedregosa et al. 2011) for Python was used using the TF-IDF Vectorizer class. It calculates the importance of a term in a sentence compared to the importance across the whole collection of sentences.

TF measures the frequency of a single term in the sentence that it is in. If the stemmed word *decarbon* is present 2 times in a sentence of 10 words, it has a TF of 0.2.

$$TF(t) = \frac{Count\ of\ term\ t\ in\ a\ sentence}{Total\ number\ of\ terms\ in\ sentence}$$

IDF measures the importance of a term considering the whole collection of sentences. It is calculated based on the number of sentences containing the term using eq.2. If *decarbon* is present in 10 of 200 sentences, then it has an IDF score of 1.3.

$$IDF(t) = \log_e\left(\frac{Total\ number\ of\ sentences}{Total\ number\ of\ sentences\ with\ term\ t\ in}\right)$$

Multiplying the TF and the IDF scores gives the TF-IDF score for the individual term. For the *decarbon* example it gives a TF-IDF score of 0.2*1.3 = 0.26. The TF-IDF analysis was then run on all the sentences describing the measures within a single sector, thereby giving the top terms describing the measures within that sector. The 10 most descriptive terms was chosen based on the highest TF-IDF scores for each sector.

2.3 Scope and limitations

Reviewing the NECP plans describe what and how the MS's plan to transition their energy supply, but not necessarily which measures that will be implemented. It is not certain that exactly the measures described here will be realized, either due to political, practical or other concerns. The approach in this article also only investigates the content of the NECP plans and not what measures the MS's already have in place and have left out of the plans. Therefore it is difficult to conclude the ambitions of certain countries only based on the data in this article. Ambitious countries might already have implemented significant low-carbon measures. Therefore, the data presented in this article illustrate how the MS's orient themselves and how they plan to move forward with decarbonisation of their energy supply.

Another limitation concerns the data collection and the empirical material itself. First, it was time and labour intensive to go through the published plans which meant it was necessary to beforehand decide on how to categorise the data and which parts of the NECP's were important. While the categories were adjusted while collecting data, they still shaped how the data entries were grouped.

The analysis of the policies and measures relies on two analytical measures. First, as described above, a count of the measures and their categories is used to estimate which types of measures is used. On a European scale, it gives a good estimate of the focus in the different sectors, but it is still uncertain as the number of measures does not necessarily describe their effectiveness. Second, this is combined with the TF-IDF analysis, which aim at identifying the terms describing the body of text best. These terms must then be interpreted as they are presented outside of their original sentences.

3 Goals and Targets for Renewable Energy and Energy Efficiency Towards 2030

This section presents the recorded goals and targets for GHG emission reductions, renewable energy and energy efficiency in the NECP's towards 2030. The targeted share of renewable energy in energy supply is reported for overall energy supply, electricity, heating & cooling and transport.

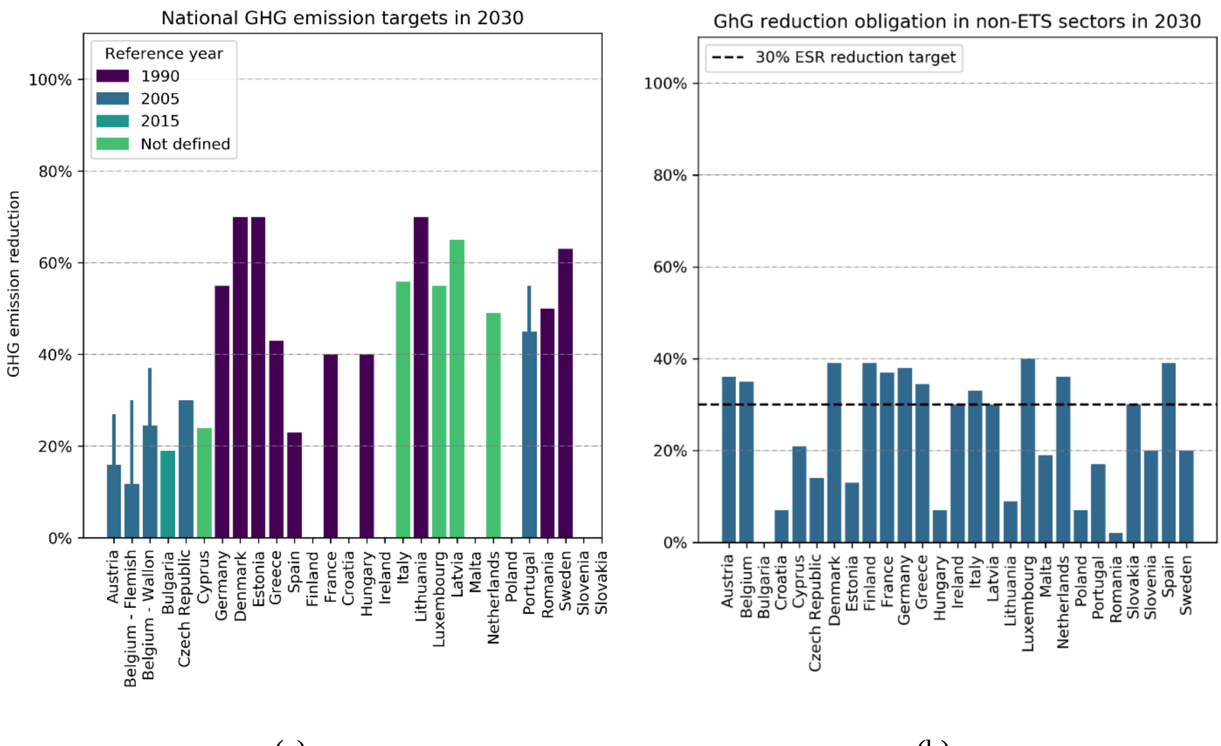
3.1 Greenhouse gas emission targets in 2030

GHG emission reductions are governed by the EU in the EU Emission Trading System (ETS) and by the Effort Sharing Regulation (ESR) covering those sectors not covered by the EU-ETS. The EU-ETS system is planned to achieve a 43% reduction in GHG emissions by 2030 with a 30% reduction planned in the ESR. (European Commission 2021a). These targets are likely to be revised to meet the new 55% reduction target.

Figure 3.1 (a) illustrate the national GHG emission reduction targets for those countries who have reported such goals in the NECP. These targets are not mandatory to define from by EU governance, but several MS's have nevertheless done so independently and reported them in the NECP's. The goal for Luxemburg and Sweden are defined outside the ETS sector, while the remaining target apply to the overall GHG emissions in the respective MS. Generally, Scandinavia and the Baltic countries have ambitious targets, with Denmark, Estonia and Lithuania all aiming at a 70% reduction in GHG emission by 2030 compared to 1990. Latvia aim at a 65% GHG reduction in 2030 without defining the reference year. Sweden aim at a 63% GHG emission reduction in the non-ETS sectors by 2030 compared to 1990.

Figure 3.1 (b) show the mandatory targets under the ESR. The ESR targets are determined based on GDP with a cost-effectiveness adjustment for MS's with above average GDP per capita.

The weighted average of the ESR targets is 31% GHG emission reduction in 2030, 1% above the EU target. The ESR targets range from Luxembourg with the highest target of a 40% reduction in 2030 followed by Denmark, Finland and Spain all with reduction targets of 39%. Ireland, Latvia, Slovakia, Italy, Greece, Belgium, Austria, Netherlands, France, Germany all have targets above or equal to 30% GHG emission reductions. Estonia, Czech Republic, Portugal, Malta, Sweden, Slovenia, Cyprus are subject to GHG emission reduction targets between 10% and 21%, while Bulgaria, Romania, Croatia, Hungary, Poland and Lithuania all have GHG emission reduction targets below 10%.



(a) (b)

Figure 3.1 (a) illustrate the greenhouse gas emission reduction targets for those MS's who have adopted national reduction targets. Figure 3.2 (b) show targets for greenhouse gas emission reductions under the Effort Sharing Regulation and concerns the sectors not covered by the EU-ETS.

Austria, Spain and the Belgian regions Flanders and Wallonia have reported lower national GHG emission targets than their mandatory ESR goals, and while their emission reduction still can be achieved in the ETS sector it signals a need to increase GHG emission targets in the future. Most other national GHG emission reduction targets are more ambitious than the ESR targets, indicating that the ESR targets could be increased.

3.2 Targets for renewable energy in 2030

Figure 3.3 show the recorded targets per MS in the EU for the share of renewable energy in either their overall energy supply or in the energy sector, depending on how the goal is formulated. The average renewable energy target, calculated as a weighted average is 33%. The European Commission has also reported that the NECP's outline targets that together fulfil the mandatory renewable energy target for the EU. Sweden has the highest target for overall share of renewable energy in 2030 at 65%. Denmark and Estonia also report a 65% share of renewable energy in final energy consumption as an ambitious scenario, but list 55% and 50% as the main target. Finland and Latvia also targets 50% or more renewable energy in their final energy supply in 2030. Austria, Croatia, France, Germany, Greece, Lithuania, Portugal and Spain all report targets above or equal to the 32% level that is mandatory for the EU as a whole. Belgium, Bulgaria, Cyprus, Czech Republic, Hungary, Ireland, Italy, Luxembourg, Malta, The Netherlands, Poland, Romania, Slovakia and Slovenia all report renewable energy targets lower than 32% in 2030, although Belgium and Ireland have ambitious scenarios that go above 32%.

The recorded targets for renewable energy in electricity supply are presented in Figure 3.4. The weighted average of all the electricity targets is 52% across the 27 MS. Only Poland does not report a target specifically for the share of renewable energy in electricity supply in their NECP. Denmark has the most ambitious target, which is to reach 100% renewable energy in electricity supply in 2030, followed by Sweden at 83% and Portugal at 80%. Croatia, Finland, Germany, Greece, Ireland, Italy, Latvia, The Netherlands and Spain all report targets above or equal to 50% renewable electricity in 2030. Belgium, Bulgaria, Estonia, France, Lithuania, Luxembourg and Slovenia all target between 30% and 50% renewable energy in electricity supply in 2030, while Austria, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania and Slovakia reported targets below 30%.

Figure 3.5 show the targets for renewable energy in heating and cooling supply as well as for district heating in the 27 MS. The weighted average for heating and cooling supply is 33%. For the four countries that have reported specific renewable energy goals for district heating, the average is 69% in 2030 for the district heating supply. For renewable energy targets in district heating, Lithuania report a target of 90%, Denmark and Estonia 80% and Finland 50%. For heating and cooling in general, Sweden reports the highest target at 72%, followed by Lithuania at 68%, Estonia at 63%, Finland at 61%, Denmark at 60% and Latvia at 58%. Bulgaria, Croatia, Cyprus, Czech Republic, France, Greece, Italy, Luxembourg, Portugal, Slovenia all report renewable energy targets for their heating and cooling supply between 30% and 50%, while Austria, Belgium, Germany, Hungary, Ireland, Malta, Poland, Romania, Slovakia, Spain report targets below 30%. The Netherlands have not reported a renewable energy target for their heating and cooling supply.

Figure 3.6 show the MS's targets for renewable energy in the transport sector for 2030. The weighted average of the targets of the 27 MS's is 15%, excluding Belgium and The Netherlands which have not submitted national targets for the share of renewable energy in the transport sector. Sweden and Finland have significantly higher goals than the remaining countries targeting respectively 47% and 45% renewable energy in the

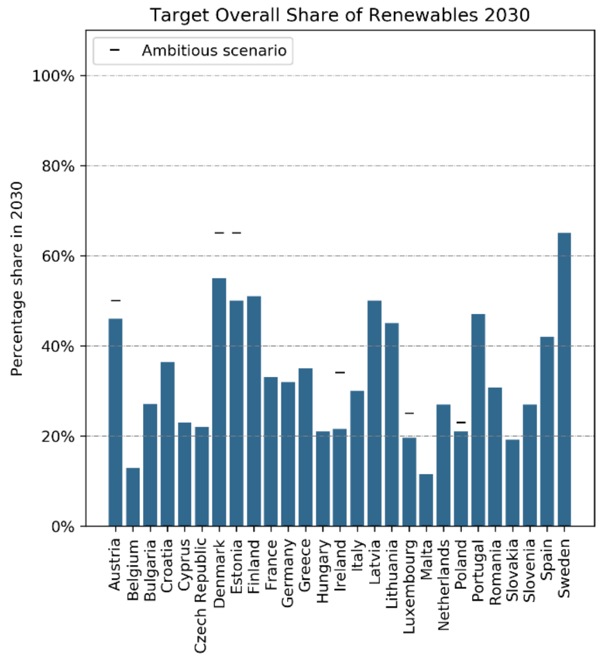


Figure 3.3 Targeted share of renewable energy in overall energy supply or in the energy sector

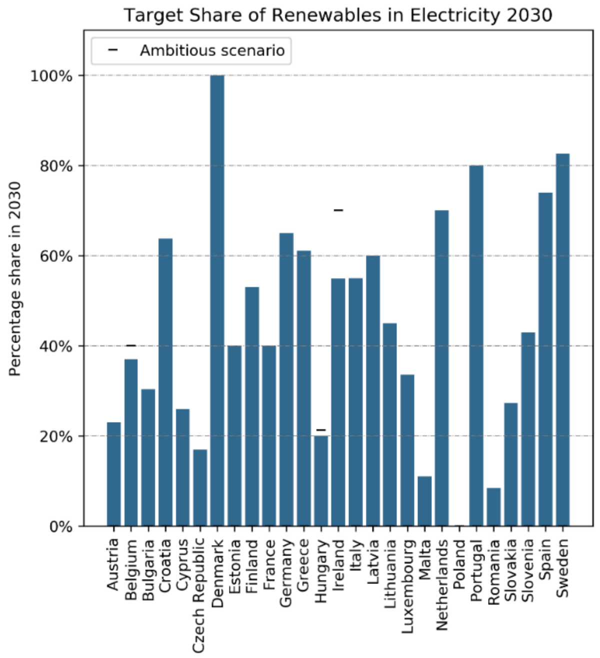


Figure 3.4 Targeted share of renewable energy in electricity supply in 2030

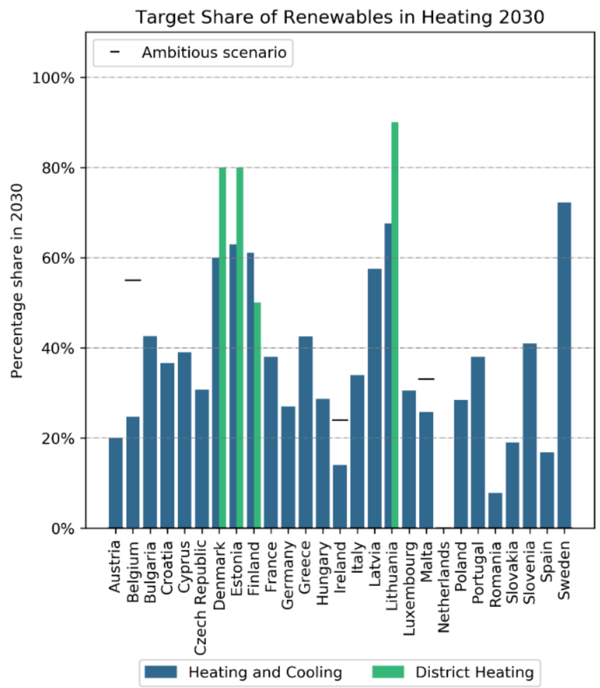


Figure 3.5 Targeted share of renewable energy in heating & cooling and district heating supply 2030

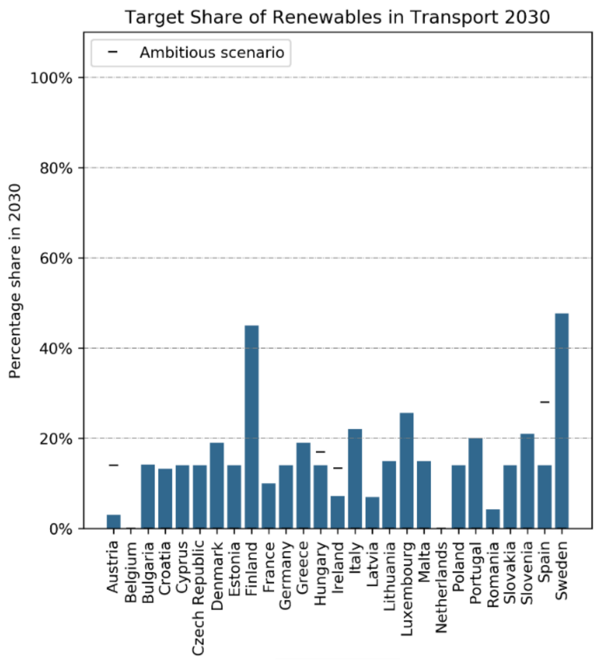


Figure 3.6 Targeted share of renewable energy in transport 2030 (Belgium report a target of 14% biofuels in transport in 2030)

Note: MS's with a 0% target indicates that no target was found in the NECP and not that the target is 0%

transport sector by 2030. Luxembourg, Italy, Slovenia and Portugal have all reported targets higher or equal to 20%. Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Lithuania, Malta, Poland, Slovakia and Spain, in total 15 MS's report targets between 10% and 20% of renewable energy in the transport sector by 2030, with Austria, Ireland, Latvia and Romania reporting targets below 10%.

3.3 Targets for energy efficiency in 2030

Figure 3.6 below illustrate the relative difference between the average primary and final energy consumption between 2015 and 2019 and the targeted primary and final energy consumption in 2030. Malta is not included in the figure due to inconsistencies between the reported data in the NECP and in Eurostat. This illustrates the MS's targeted development of energy consumption towards 2030. It also allows for comparison between the MS's and their targets, something that was not possible given the current reporting scheme of energy efficiency targets in the NECPs. The analysis shows that on average, 5% average final energy savings are targeted in 2030 compared to average 2015-2019 final energy consumption. For primary energy the targeted savings are on average 18%. This cannot be directly compared with the EU 32.5% energy efficiency target in 2030, as this is compared to a business-as-usual development of energy consumption. In absolute terms, the targeted energy consumption in 2030 is 13 PWh or 1133 Mtoe for primary energy and 10 PWh or 865 Mtoe for final energy. Both targets are below the overall EU target of 14.8 PWh or 1273 Mtoe primary energy consumption and 11.2 PWh or 956 Mtoe final energy consumption in 2030.

There is targeted a greater reduction in primary energy than in final energy towards 2030, which might be driven by a move towards renewable energy. Shifting from fossil fuels to renewable energy will eliminate combustion and in turn the related conversion losses. Other explanations can come from increased uptake of electric vehicles or use of waste and excess heat in district heating systems, all measures that would decrease primary energy consumption but keep final energy and end-use consumption stable. While such measures do result in primary energy reduction they are inherently supply measures and should not be confused with energy

Difference between primary and final energy consumption targets and 2015-2019 average

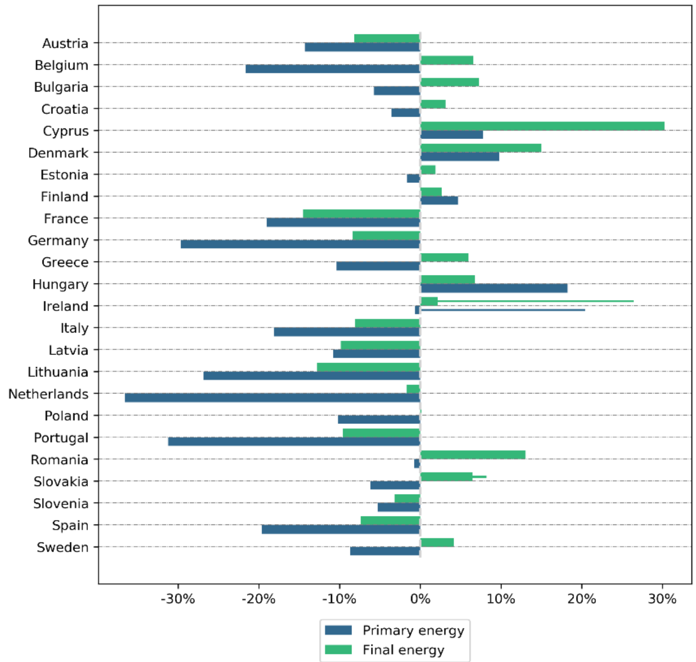


Figure 3.7 Calculated relative difference between the 2030 primary and final energy consumption reported in the NECPs and 2015-2019 average primary and final energy consumption reported to Eurostat.

efficiency measures targeting reductions in consumption. This highlights that the NECPs could increase focus on specific energy efficiency improvements targeting end-use and final energy reductions.

4 Policies and Measures in the National Energy and Climate Plans Towards 2030

This section presents the results of the analysis of which policies and measure the 27 MS's aim to deploy in order to achieve the goals in the EU regulation, including the targets outlined in the section above. Figure 4.1 presents the identified sectors in the NECPs. These are *Societal*, *Electricity*, *Transport*, *Energy Sector*, *Buildings*, *Fuels*, *Heating & Cooling*, *Industry* and *Agriculture*. Most measures have a *Societal* focus, with over half of the measures from the *Decarbonisation* dimension. The second most addressed sector is *Electricity*, with close to half of the measures from *Decarbonisation* dimension. *Energy Efficiency* and *Research*, *Innovation and Competitiveness* have the most measures after *Decarbonisation. Energy Security* and *Internal Energy Market* are the least addressed dimensions measured in number of measures regarding the *Electricity* sector. *Energy sector* comes third. Almost half of the measures addressing the *Energy Sector* category comes from the *Decarbonisation* dimension. *Internal Energy Market* is the dimension with the second most measures, and *Energy Efficiency*, *Energy Security* and *Research*, *Innovation and Competitiveness* all share equal parts. *Transport* is the fourth sector in number of measures. It is mostly made up of measures from the *Decarbonisation* dimension. *Buildings* is the fifth most addressed sector, with a significant amount of the measures coming from the *Energy Efficiency* dimension. *Decarbonisation* takes most of the remaining measures. *Fuels* is the sixth most addressed sector, with a high share of the measures from the *Energy Security* dimension. *Heating and Cooling* comes seventh when counted on number of measures, and is almost entirely made up of measures from the *Decarbonisation* dimension. The sectors ends with *Industry* with measures from *Decarbonisation* and *Energy efficiency* dimensions and *Agriculture,* with measures mostly from the *Decarbonisation* dimension.

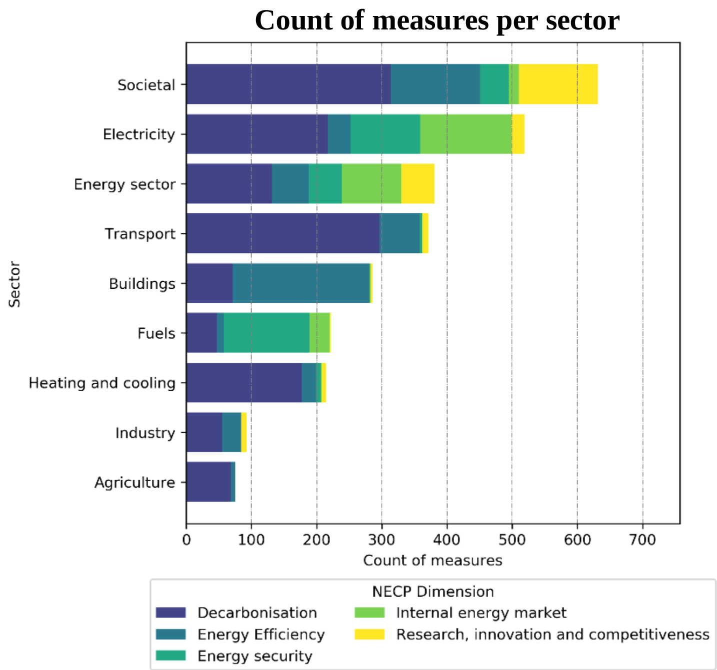
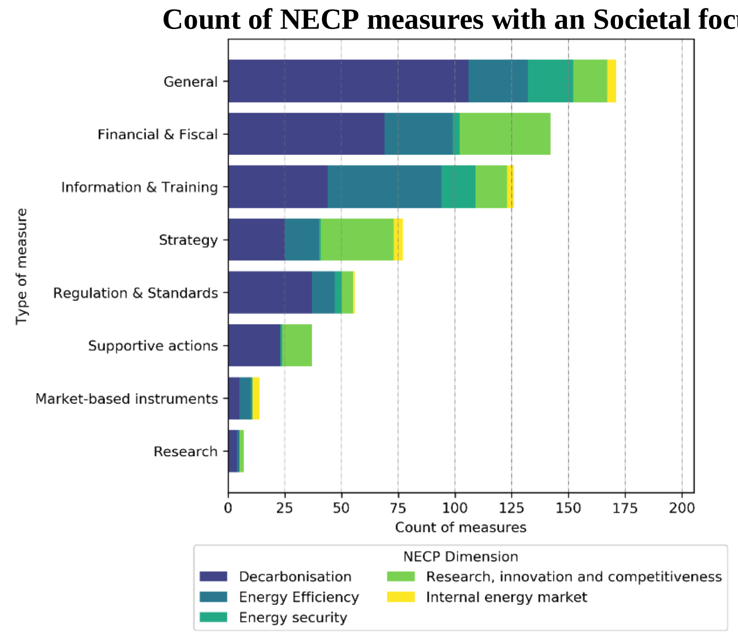


Figure 4.1 Count of recorded measures in all of the 9 sectors identified. The colors show which NECP dimensions the measures address.

4.1 Societal measures



10 highest ranked terms from TF-IDF analysis

'providing', 'publicly', 'training', 'services', 'promotion', 'developments', 'energy', 'introducing', 'measuring', 'schemes'

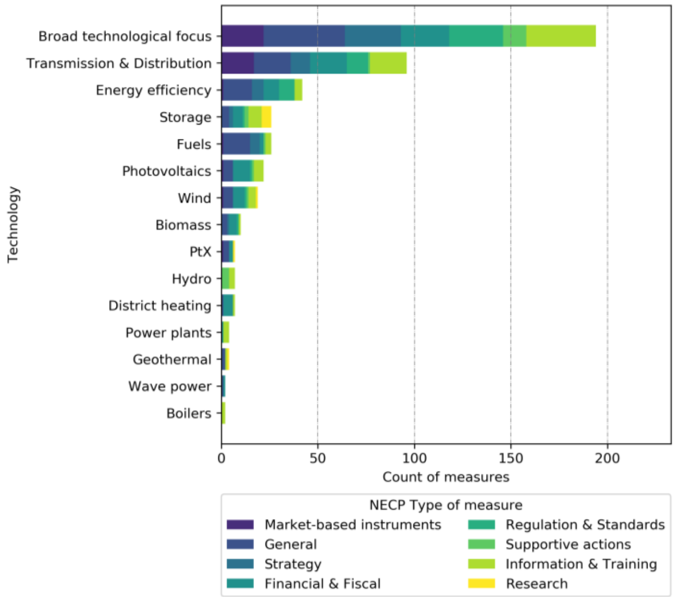
Figure 4.2 Count of recorded measures with a societal focus showing the type of measure and the NECP dimension addressed

Figure 4.2 above shows the types of measures with a *societal* focus, with the bars being split into the different NECP dimensions. The results of the TF-IDF word analysis show that the measures with a *societal* focus, not surprisingly, has a broad focus. A number of terms indicate the governance work ahead with terms like *providing, training, services, developments, introducing, measuring* and *schemes*. *Energy* describes the central contents of these plans and the term *Publicly* suggest the important role of involving the public in the energy transitions.

Of the 631 total measures with a *societal* focus, most measures are of the *General* type with 171 recorded. *General* measures include but are not limited to aims to cooperation across borders, partnerships, regional or local climate plans or increasing participation of citizens, SME's and local authorities in the energy transition. There is a certain degree of cooperation and attempts to promote collective action in the *General* measures. 62% of the *General* measures come from the *Decarbonisation* dimension. *Financial & Fiscal* is with 142 recorded measures the second most used type of measure with a *societal* focus. The *Financial & Fiscal* measures are spread between the dimensions with 49% *Decarbonisation*, 21% *Energy Efficiency*, 28% *Research*, *Innovation* and *Competitiveness* and 2% for the *Internal Energy Market*. *Financial & Fiscal* measures include subsidies, loans, funds, taxation, CO_2 pricing, EU funds such as the Structural Funds, Invest EU Programme or the Modernisation Fund. *Information & Training* measures include 126 measures, with 40% in the *Energy Efficiency* dimension, 35% in *Decarbonisation,* 12% in *Energy Security*, 11% in *Research, Innovation and Competitiveness* and 2% in the *Internal Energy Market.* The measures includes utility companies and energy suppliers providing energy metering, educating new skilled labor and information campaigns aimed at increasing energy efficient behavior. The 77 *Strategy* measures are spread between 42% *Research, Innovation and Competitiveness*, 33% in *Decarbonisation*, 20% in *Energy Efficiency*, 5% *Internal Energy Market* and 1% in *Energy Security.* The *Strategy* measures address a wide range of topics such as energy security, technology innovation, air pollution reductions but all encompass future action to be taken up by MS governments or other related actors. There are 56 recorded measures in *Regulation & Standards* with 66% from the *Decarbonisation* dimension, 18% from *Energy Efficiency*, 9% from *Research, Innovation and Competitiveness*, 5% from *Energy Security* and 2% from *Internal Energy Market. Regulation & Standards* includes mandatory use of equipment, monitoring of energy use and emissions, restricting the use of certain fuels but also granting permits for renewable deployment and adoption of new technologies. The remaining types of measures are *Supportive Actions* with 37 measures, *Market-Based Instruments* with 14 and *Research* with 7.

4.2 Electricity sector

Count of NECP measures in the Electricity sector



10 highest ranked terms from TF-IDF analysis

'companies', 'gradually', 'energy', 'allowing', 'meters', 'consumers', 'available', 'smart', 'new', 'storage'

Figure 4.3 Count of recorded measures in the Electricity sector showing the Technology category and the type of measure used

Figure 4.3 show how the measures recorded in the *Electricity* sector are spread between different technologies and which measures are taken for each type of technology. The TF-IDF word analysis show that the *electricity* sector measures are concerned with *companies* and *consumers* taking part of the development. *Meters* and *smart* signify a move towards smart grids and flexible consumption using *new* and *available* technologies and data. *Storage* seems to be the only specific *energy* technology mentioned. A few terms describe the governance and transitions using words like *gradually* and *allowing*.

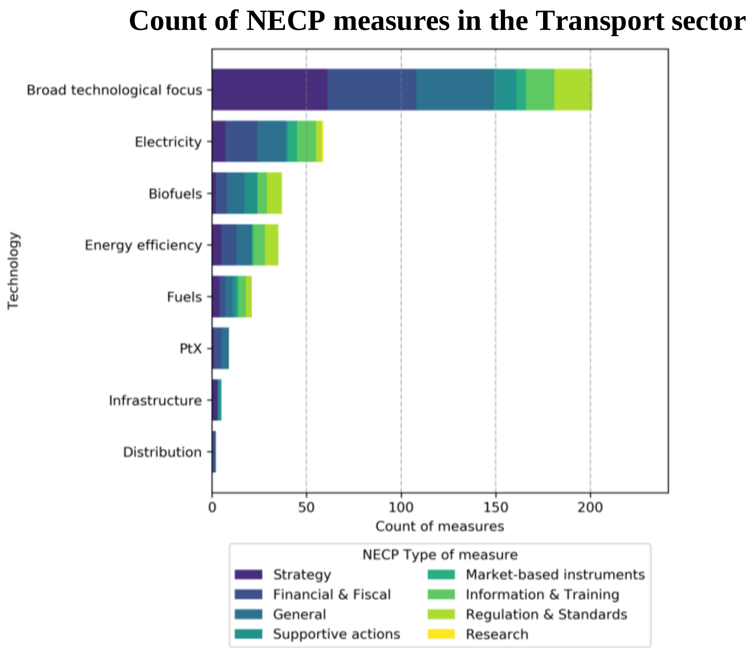
There are recorded a total of 519 measures in the *Electricity* sector, with 205 classified with a *Broad Technological Focus*. The *Broad Technological Focus* measures being deployed by the MS's are 23% *General* measures, 18% *Information & Training*, 17% *Strategy,* 14% *Regulation and Standards*, 12% *Financial & Fiscal,* 11% *Market-based Instruments* and 6% *Supportive Actions.* Examples of the *Broad Technological Focus* category include flexibility measures, operating support, electricity generation but from multiple sources such as biofuels, hydropower and photovoltaics, household level electricity generation, guarantees of origin, smart meters or annual auctions.

The second technological category is *Transmission & Distribution* with 96 measures. Most measures in the *Transmission & Distribution* category are *Information & Training*, *General* and *Financial & Fiscal* each at 20%, followed by *Market-based Instruments* with 18%, and 12% *Regulation & Standards*, with *Strategy* and *Supportive Actions* each at 10%. The *Transmission & Distribution* category focuses on promoting real-time trading of electricity, connecting national grids to smaller distribution grids, energy market organisation, electricity market aggregators and the participation of storage units on electricity systems.

Energy Efficiency is the third most recorded technology in the *Electricity* sector with 33 recorded measures. *General* measures have the largest share with 33% followed by *Regulation & Standards* and *Financial & Fiscal* at 24% each. *Information & Training* account for 12% with *Market-Based Instruments* and *Strategy* each at 3%. Measures for *Energy Efficiency* focus on replacing old transformers, electricity grid improvements, LED lighting and monitoring, data and measurements.

Storage and *Fuels* has 26 recorded measures, *Wind* with 19 and *Biomass* with 10. The remaining technological categories all have below 10 recorded measures.

4.3 Transport Sector



10 highest ranked terms from TF-IDF analysis

'transported', 'efficient', 'rail', 'sectors', 'energy', 'measures', 'promotions', 'publicly', 'order', 'economy'

Figure 4.4 Count of recorded measures in the Transport sector showing the Technology category and the type of measure used

371 measures are recorded in the *Transport* sector, and Figure 4.4 show how they are distributed across the technology categories. The results of the TF-IDF word analysis highlights a transition towards *efficient* transport with the terms *economy, rail* and *sectors* describing some important areas and technologies. *Transported* and *energy* describe the primary contents, and *publicly, promotions, order* and *measures* describe governance action.

The most used technology category is *Broad Technological Focus* with 201 recorded measures. *Strategy* is the most used measure with 30% of the measures, followed by *Financial & Fiscal* measures at 23%, *General* measures at 20% and *Regulation & Standards* at 10%. *Information & Training*, *Supportive Actions* and *Market-based Instruments* account for 8%, 6% and 3% respectively. Measures in the *Broad Technological Focus* category include spatial planning, evaluating flexible work hours, taxation and raising awareness of the benefits from energy efficient driving and aims to increase public transport and modernization of the vehicle fleet.

Electricity is the second most recorded technology in the *Transport* sector with 59 measures. *Financial & Fiscal* measures account for 29%, *General* account for 25% and *Information & Training* for 17%. The remaining measures are 12% *Strategy,* 9% *Market-Based Instruments,* 5% *Regulation & Standards* and 2% *Research*. The main focus of the *Electricity* technology category is electric vehicles and the roll out of related infrastructures particularly in terms of charging stations. This is done with measures to promote electric vehicle sales, amending taxation to reflect CO_2 emissions, billing schemes for households with charging stations and information systems about charging infrastructure. Other measures address the electrification of railways, freight transport and public transport.

Biofuels is with 37 recorded measures the third technological category. *General* measures and *Regulation & Standards* and respectively take up 24% and 21% of the measures. *Financial & Fiscal* measures account for 16%, Supportive Action for 19% and *Information & Training* for 14% share. *Strategy* measures are at 5%. Aims include mixing biofuels in fuel supply, using biofuels in heavy transport, aviation and freight, and increasing domestic production of fuels.

The fourth most mentioned technological category in the *Transport* sector is *Energy Efficiency* with 35 measures. *General* and *Financial & Fiscal* measures are both at 23%, followed by *Regulation & Standards* at 20% and *Information & Training* at 18%. *Strategy* measures take up 14% and *Market-based Instruments* are 3% of the *Energy Efficiency* measures in the *Transport* sector. The *Energy Efficiency* measures include attempts to increase shared mobility and public transport to decrease energy consumption, introduction of circular economy principles, renewal of vehicle fleets, campaigns and tax reforms to promote modal shifts. There is both a focus on the decrease of energy consumption through changing mobility patterns, increasing shares of public transport and shared mobility as well as using shifts to new low-carbon fuels in order to reduce the use of fossil fuels in transport.

The *Fuels* category includes 21 measures, and mostly focus on changing current fuel supply to other forms of fuels including both LNG and renewable fuels. The *Infrastructure* category includes 5 measures and is concerned with the creation of new routes and upgrade of existing ones, introducing mobility hubs and metro expansion. *PtX* had 9 recorded measures, *Infrastructure* has 5 and *Distribution* has 2.

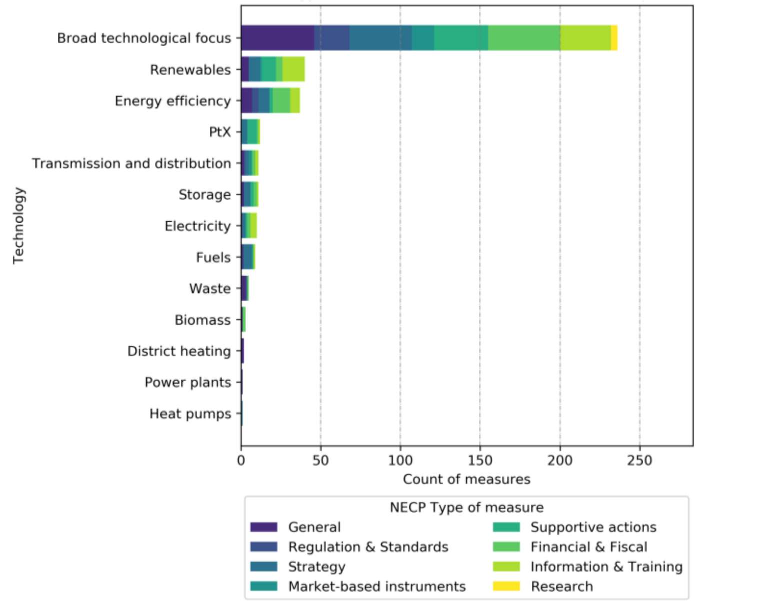
4.4 Energy sector

As Figure 4.5 shows, the *Energy Sector* has 381 recorded measures and these are mostly of the *Broad Technological Focus* measure type with 235 in this category. As the category *Energy Sector* in itself is a combination of several technologies, transmission and distribution infrastructure as well as end-users, it makes sense that most measures does not address a single technology but are grouped in the *Broad Technological Focus* category. This is also reflected in the results of the TF-IDF word analysis where the terms *savings*, *efficient* and *res* (renewable energy supply) highlight the envisioned changes in the *Energy Sector*, while *strategy*, *informing*, *aims*, *changing* describe some of the proposed ways forward and necessary changes. *Publicly* and *nationally* illustrate the scope of measures concerning the *Energy Sector* being important to involve the public but also address energy supply on a national scale, *climate* describe the overall goal and motivation for the measures.

The *Broad Technological Focus* category is made up of the following measures. 20% of General, 19% Financial & Fiscal 17% Strategy, 15% Supportive Actions, 13% of Information & Training, 9% Regulation & Standards, 6% Market-based instruments and 2% Research. The *Broad Technological Focus* measures in the *Energy Sector* aims to develop a combination of photovoltaics, wind power, storage, biofuel production and smart grid projects, aggregating electricity producers to participate in electricity markets, use the Mission Innovation initiative, digitalising the energy system, and move towards competitive financial support systems.

40 measures are recorded in the *Renewables* category, with 35% of the belonging to *Information & Training*, 23% to *Supportive Actions*, 18% to *Strategy*, 13% to *General*, 10% to *Financial & Fiscal* and 2% *Market-based instruments*. The measures are targeted at for example developing frameworks for the use of biomass and biofuels, tax reforms for biogas and hydrogen production, assessment of technical potentials and implementation of wind and solar energy as well as incentives for SME's, citizens and office buildings.

Count of NECP measures in the Energy sector



10 highest ranked terms from TF-IDF analysis

'strategy', 'savings', 'changing', 'climate', 'aims', 'informing', 'nationally', 'publicly', 'res', 'efficient'

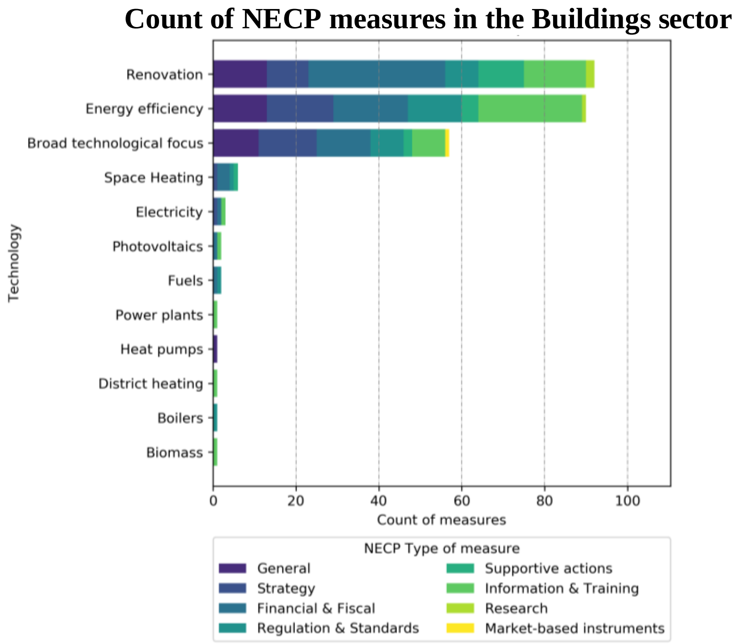
Figure 4.5 Count of recorded measures in the Energy sector showing the Technology category and the type of measure used

Energy Efficiency is the third technology category with 37 recorded measures. *Energy Efficiency* measures in the *Energy Sector* category are made up of 30% *Financial & Fiscal* measures, 19% *Strategy* and *General* measures each, 16% *Information & Training*, 11% *Regulation & Standards* and 5% *Supportive Actions*. Measures include mandatory energy savings to be implemented by energy companies and energy performance contracts. Measures are taken to increase energy efficiency and the uptake of renewable energy to improve security of supply among other benefits and using financial instruments to promote energy efficiency measures. Several technology specific measures have also been recorded with *PtX* at 12, *Transmission & Distribution* and *Storage* at 11 and the remaining technology categories at 10 or below.

4.5 Buildings

The *Buildings* sector has 286 recorded measures as illustrated in Figure 4.6, mostly spread between the technology categories of *Renovation*, *Energy Efficiency* and *Broad Technological Focus*. The TF-IDF word analysis identifies several terms describing the need to involve the *consumers* in making changes in the building sector such as *introducing, involving*, *making* and *encouraging*. *Directly, investments, new, implemented, efficiently* also describe the needed changes and how they are envisioned to happen.

Renovation is the most recorded approach in the *Buildings* sector with 92 measures. These are made up of 36% Financial & Fiscal, 16% Information & Training, 14% General, 12% Supportive Actions, 11% Strategy, 9% Regulation & Standards and 2% Research. The measures include incentives for homeowners to renovate, improvement of knowledge of house owners and the professionals carrying out the renovations, public strategies for mapping housing conditions and renovation potentials.



10 highest ranked terms from TF-IDF analysis

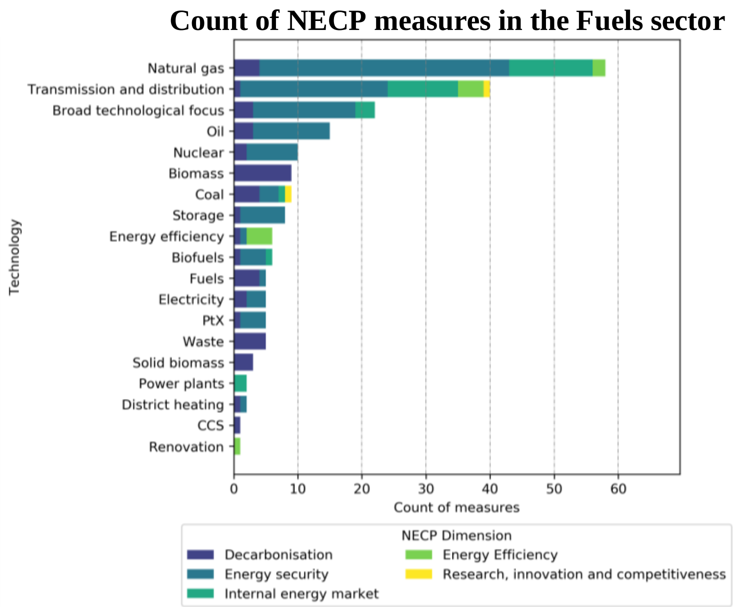
'directly', 'introducing', 'involving', 'consumers', 'making', 'encouraging', 'investments', 'implemented, 'new', 'efficiently'

Figure 4.6 Count of recorded measures in the Building sector showing the Technology category and the type of measure used

Energy Efficiency closely follows *Renovation* with 90 recorded measures. *Information & Training* is with 28% the most used measure in this category. *Financial & Fiscal* follows with 20% and *Strategy* measures have an 18% share. *General* and *Regulation & Standards* measures take up 14% each, 4% *Supportive Actions* and 1% *Research*. While *Energy Efficiency* and *Renovation* measures are closely related, they still differ as *Energy Efficiency* includes a broader approach to decreasing energy consumption in the *Buildings* sector. The *Information & Training* measures includes a particular focus on public buildings and their users, and expanding on training on how to save energy. The category also includes several strategies, for example on how to increase the number of low energy houses or NZEBs (nearly zero-energy buildings). Other measures focus on the improvement of existing building stock, monitoring, periodic reviews and data collection or using energy efficiency measures as a tool for urban and rural regeneration.

The *Broad Technological Focus* category has 57 recorded measures in the *Building* sector. *Strategy* is the most recorded measure in this category with 25% of the measures, followed by 23% *Financial & Fiscal*, 19% *General*, 14% *Information & Training* and *Regulation & Standards* each, 4% *Supportive Actions* and 2% *Market-Based Instruments* each. The high *Strategy* share is expressed in the measures with a focus on promoting low-energy buildings and NZEBs, improving circular economy principles, promoting innovative housing concepts as well as giving a central role of cities in increasing energy efficiency. Financing through public funding, taxation, changes in VAT rates are all part of the measures. All the remaining technological categories have below 10 recorded measures.

4.6 Fuels



10 highest ranked terms from TF-IDF analysis

'optimizing', 'integration', 'service', 'flexible', 'transportation', 'conditions', 'existing', 'promotion', 'aims', 'projects'

Figure 4.7 Count of recorded measures in the Fuels sector showing the Technology category and the NECP Dimension addressed.

The *Fuels* sector has 222 recorded measures. Figure 4.7 illustrate the NECP dimensions that each recorded measure address for each technology category. A central point for the *Fuel* sector is their importance in the *Energy Security* dimension, as this dimension is where most of the *Fuel* measures were recorded. The TF-IDF word analysis show a focus on *optimizing*, *integration* and *flexible* fuels and energy supply. *Transportation* highlights a focus on transmission and distribution infrastructures while *service* illustrate the need to maintain energy services and security. *Promotion, aims, projects* illustrate the need for new developments while *existing* and *conditions* point towards the infrastructures and the context already in place.

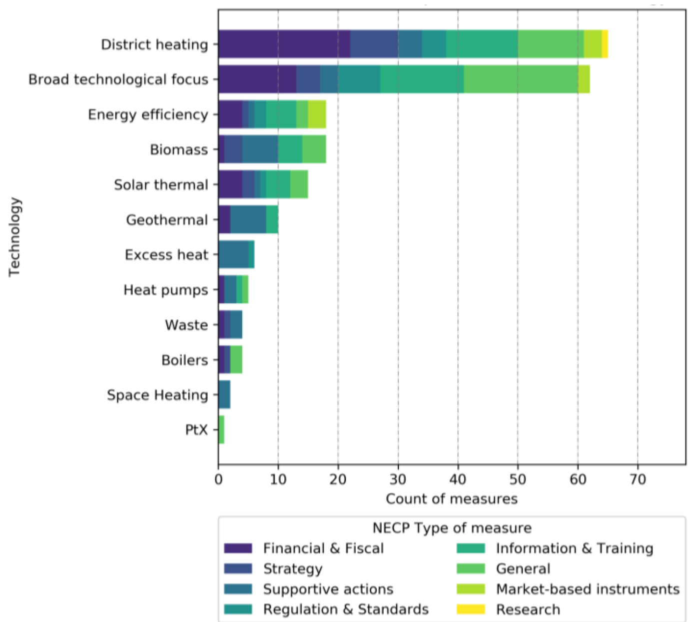
Natural Gas is the most recorded fuel with 58 measures. 67% of the measures are from the *Energy Security* dimension, followed by 22% *Internal Energy Market*, 7% *Decarbonisation* and 3% *Energy Efficiency*. Several of the measures focus on maintain energy supply form gas, establishing storage or expanding gas infrastructures. In a combination of both *Energy Security* and the *Internal Energy Market*, several measures focus on establishing cross-border gas transmission infrastructure as part of the Projects of Common Interest (PCI) list. Several measures encourage the use of domestic resources to increase *Energy Security.*

Of the 40 recorded measures in the *Transmission & Distribution* category, 58% of them are from the *Energy Security* dimension. The *Internal Energy Market* follows with 28%, 10% *Energy Efficiency*, and 3% of *Decarbonisation* and *Research, Innovation and Competitiveness* each. Most of the measures focus on expanding natural gas infrastructure to interconnect supply systems and to increase energy security. National TSO's are central actors in this work as they monitor, plan and carry out many of the investments. Regulatory and supportive measures are being planned in order to facilitate the investments into natural gas infrastructure.

The *Broad Technological Focus* category has 22 measures split between 72% *Energy Security* and 14% of *Decarbonisation* and *Internal Energy Market* each. Some measures focus on reducing natural gas consumption by encouraging use of alternative gas sources, the use of biomass or increasing the use of CHP plants. Emergency energy preparedness plans, and making safeguard plans for natural gas supply also constitute a part of the measures in this category. There are 15 recorded measures for *Oil*, 10 for *Nuclear*, and below 10 for the remaining technologies.

4.7 Heating & Cooling sector

Count of NECP measures in the Heating & Cooling sector



10 highest ranked terms from TF-IDF analysis

'purposes', 'continue', 'distribution', 'aid', 'construction', 'existing', 'investments', 'new', 'supports', 'district'

Figure 4.8 Count of recorded measures in the Heating & Cooling sector showing the Technology category and the type of measure used

Figure 4.8 illustrate the 215 recorded measures in the *Heating & Cooling* sector. The TF-IDF word analysis identified both a focus on *new* and *existing* measures and solutions. *District* and *distribution* highlight the focus on district heating infrastructures while *new*, *investments*, *aid* and *supports* illustrate some of the necessary measures. There is also a focus on *continue* measures already in place to fulfil the *purposes* in the NECP's.

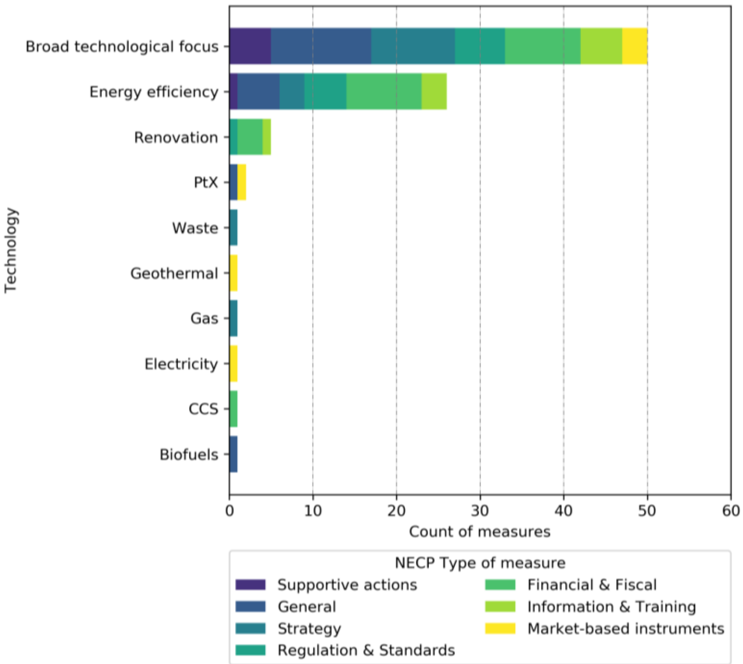
There are 66 recorded measures about *District Heating*, with 34% *Financial & Fiscal* measures, 19% *Information & Training*, 17% *General*, 12% *Strategy*, 6% *Supportive Actions* and *Regulation & Standards* each, 5% of *Market-Based Instruments* and 2% *Research*. The measures mention district heating as having a potential to increase energy efficiency, decreasing the dependence on fossil fuels including moving away from for example oil boilers. New legislation, new public strategies, new funding changing taxation and VAT rates are mentioned as some of the measures to implement district heating networks and utilize heat pumps, CHP, waste heat and other potential heat sources for district heating systems.

The *Broad Technological Focus* category is with 62 recorded measures the second most used category. It is made up of 23% *Information & Training*, 20% *General*, 18% *Financial & Fiscal*, 12% of *Regulation & Standards* and *Other* each, 7% *Strategy*, 5% *Supportive Actions* and finally 3% *Market-Based Instruments.* A central focus of the *Broad Technological Focus* measures is how to promote investments in and implementation of new low-carbon heating equipment. One approach is to highlight technological potentials and benefits through communication channels, training and information campaigns. Support for new technologies, new pricing, taxation, VAT rates and public funding is mentioned. Local authorities such as municipalities are mentioned as important stakeholders in implementing new heating technologies, while the funding sources often are national funds, taxation schemes or based on EU financing.

The remaining technological categories in the *Heating & Cooling* sector are *Energy Efficiency* with 19 measures, *Biomass* with 18, *Solar Thermal* with 15, *Geothermal* with 10, *Excess Heat* with 6, *Heat Pumps* with 5, *Boilers* with 4 and *PtX* with 1 measure.

4.8 Industry

Count of NECP measures in the Industry sector



10 highest ranked terms from TF-IDF analysis

'sharing', 'information', 'savings', 'allow', 'platform', 'voluntarily', 'requires', 'entities', 'introduced', 'creation'

Figure 4.9 Count of recorded measures in the Industry sector showing the Technology category and the type of measure used

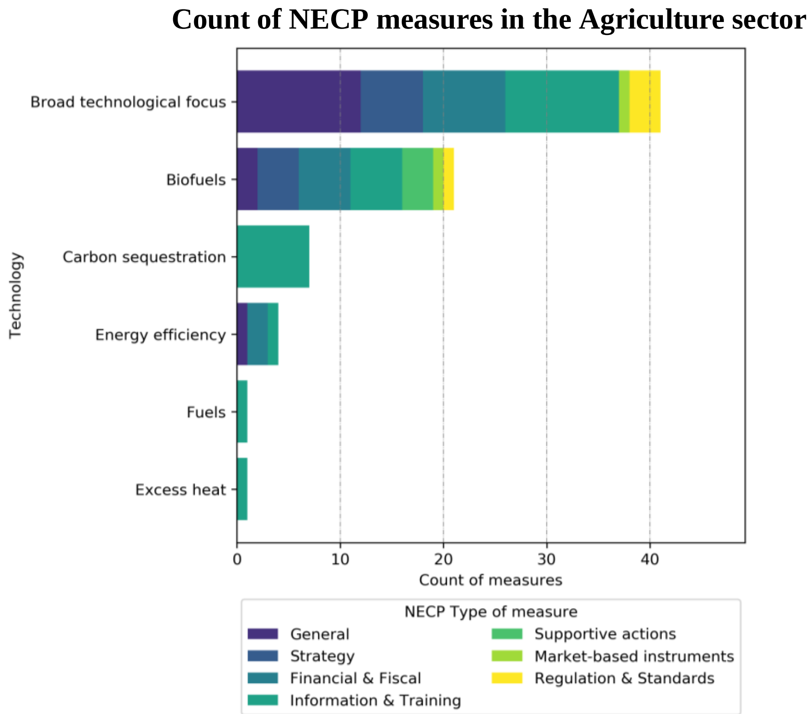
There are a total of 93 recorded measures in the *Industry* sector as shown in Figure 4.9. The TF-IDF analysis identified several terms describing the efforts and governance to promote change in the industrial sector, such as *sharing, information, allow, platform, voluntary, requires, introduced and creation.* Some of the terms indicate cooperation and voluntary action while others suggest mandatory requirements. *Savings* describe the main focus of the sector, namely to increase energy efficiency. The *entities* term suggest the fact that many different actors and businesses have to be addressed with the measures.

The *Broad Technological Focus* measure is the most frequent with 50 recorded measures. It is split between 24% *General* measures, 20% *Strategy*, 18% *Financial & Fiscal*, 12% *Regulation & Standards*, 10% each of *Support & Measures* and *Information & Training* and 6% *Market-Based Instruments*. The *Broad Technological Focus* measures include exploring trading emissions and related taxes, the reduction of greenhouse gasses as well as fluorinated gas, support for making it feasible from a business perspective to use renewable electricity and heat and implementation of circular economy principles.

The *Energy Efficiency* measure has 26 recorded where *Financial & Fiscal* is the most used with 35%. *General* and *Regulation & Standards* both have 19% each, *Information & Training* and *Strategy* both have 12% and 4% for *Supportive Actions*. The measures focus on developing the industrial sectors to transition towards an efficient and low-carbon economy, encouragements to conserve energy, do energy audits and investigate how industrial processes can be optimized.

PtX has 2 recorded measures with 1 recorded measure for each of the remaining technologies.

4.9 Agriculture



10 highest ranked terms from TF-IDF analysis

'major', 'locations', 'slurry', 'incentives', 'providing', 'residues', 'collection', 'crops', 'plants', 'biomass'

Figure 4.10 Count of recorded measures in the Agriculture sector showing the Technology category and the type of measure used

Figure 4.10 illustrate the *Agriculture* sector with 75 recorded measures. The TF-IDF analysis identified several sector specific terms such as *slurry, residues, collection, crops, plants* and *biomass* while *providing* and *incentives* describe some measures and approaches. *Major* can be interpreted as the scale of change or necessary interventions in the agricultural sector.

The most recorded type of measure is *Broad Technological Focus* with 41. They consist of 30% *General*, 27% *Information & Training* measures, 20% *Financial & Fiscal*, 15% *Strategy* and 7% *Regulation & Standards*. The measures include public procurement, investments across the sector, environmental requirements and ecological farming.

Biofuels have 21 measures, spread between 24% *Information & Training* and *Financial & Fiscal* each, 19% *Strategy*, 14% *Supportive Actions*, 10% *General* and 5% of *Market-Based Instruments* and *Regulation & Standards* each. Several measures focus on biogas production and the necessary plants and collection of biowaste. There is also a focus on the collection of wood residues from the forestry sector as well as support measures for short rotation coppic cultivation of biomass. 4 measures were recorded for *Energy Efficiency*, 1 for *Fuels* and 1 for *Excess heat.*

5 Conclusions and Policy Implications

The NECP plans reviewed in this article outline the renewable energy and energy efficiency targets towards 2030 as well as the policies and measures the 27 MS's plan to use to reach these goals. From this review, several conclusions can be drawn. First, the *Electricity* sector has the highest renewable energy targets and this is the sector where most countries have the most ambitious goals. The *Heating & Cooling* sector follows, and the targets here are largely on the same level as the overall targets for renewable energy in total energy supply. The renewable energy targets could be more ambitious for heating and cooling supply, given the fact that several proven technologies exist and are in use today. Just as intermittent electricity generation, such as wind and solar, have become widespread today, so are several supply technologies available for a renewable and efficient heating and cooling supply. Especially district heating systems are promising, as only high and ambitious renewable energy targets have been found for district heating supply. If seeing district heating as a specific sector, this has the single highest average targets of renewable energy in 2030. The *Transport* sector has the lowest targets for share of renewable energy in final energy consumption. This sector is technologically difficult to decarbonize, but as it accounts for a significant share of energy consumption it is vital to prioritize.

The *Energy Efficiency* targets are set to meet the EU goals in absolute terms. This article has not calculated if they reach the relative reduction target of 32.5% reduction in 2030 compared to a business as usual development. Instead, a comparison between the absolute energy consumption 2030 targets and reported average energy consumption between 2015 and 2019 was carried out. It shows that an 18% reduction in primary energy but only a 5% reduction in final energy is planned. This is likely due to the system effects of switching from fossil fuels to renewable energy supply which limits conversion losses and results in decreased primary energy consumption. While such a switch results in primary energy savings, it is inherently a change in supply technology and not energy efficiency measures. Therefore, the NECP's could be more ambitious with end-use and final energy savings.

Sector integration is an important topic throughout the NECP's and have a significant focus. Measures with a *societal* focus are the most used, signaling that a significant amount of measures and policies are directed at developing decarbonized and energy efficient energy supply without focusing on a particular sector. Other sector integration measures include the focus on electrification of the transport sector and the measures identified addressing the *Energy Sector* between different supply systems. Still, significant potentials are under-addressed. The *Building* and *Industry* sectors are largely focused on reducing energy consumption and not on the integration with other sectors. *Heating & Cooling* is also mostly addressed as a silo without significant interaction with other sectors, although the focus on district heating systems potentially allows for sector integration efforts through CHP, heat pumps, excess heat and other sources. Sector-integration and integrated energy system developments should consider the synergies between all sectors and end-uses and not simply focus on electrification, as this might lead to higher socio-economic costs (H. Lund 2014, 2018).

Several policies and measures address overall technological development and does not target specific technologies. The *Broad Technological Focus* category is in the top three of most addressed in all the sectors covered above. This highlights a focus in the NECP's that within the specific sectors, the MS are trying to not to choose between specific technologies. For example, within the electricity sector, there is not identified a large focus on specifically deploying wind turbines or photovoltaics, but instead on a broader group of renewable electricity generation. The NECP's still outline the role, size and purpose of the specific sectors, while, in some cases, remaining neutral to the specific technologies delivering the energy within them. Low-carbon heat can be delivered by heat-pumps, geothermal or biomass and electricity by a number of renewable sources. Still, it is still necessary to plan, specify and decide the development of the sectors and related infrastructures for each of the MS's.

This review has also identified that the *energy security* dimension and *fuels* sector still is dominated by fossil fuels and especially by plans about expanding natural gas infrastructure. Such investments in infrastructure have long life-times and will potentially be in place long after a climate neutral EU in 2050. It is also doubtful whether investments in natural gas infrastructure will constitute sunk cost in a low-carbon economy. Therefore, researchers, energy planners and public officials should focus on how energy security can be achieved from an energy system perspective in fully renewable energy systems, to explore alternatives to energy security based on natural gas.

The next round of NECP's must address the more ambitious goal of a 55% reduction in GHG emissions in 2030 compared to 1990, requiring more ambitious plans, targets and measures. A central focus forward and for the next iteration of the NECP's should be that the 27 MS's consider how the electricity, heating & cooling, buildings, transport, agriculture and industry sectors can exploit synergies and explore where limited resources such as biomass and biofuels, hydrogen and manufactured fuels most effectively should be used. Balances between renovations in the building sector and development of district heating supply should be a central focus, as well as which transport sectors are in most need of the scarce amount of liquid fuels that will be available. The first round of NECP's illustrate the significant work ahead, but also that the 27 MS's are addressing the challenges of adjusting energy supply to a low-carbon and energy efficient energy supply.

The first round of the NECP's signal the right direction but there is still much to be improved. Now the task for the MS's is to deliver on their promises and reach the NECP targets, while simultaneously increasing their energy and climate goals and ambitions, revisit the plans of fossil fuel development and exploit the remaining sector coupling potentials that are still available.

6 Appendix

Overview of categories and attributes used in the data collection.

Categories	Type of measures	Sectors	Technologies	Technologies – cont.
Attributes	'Strategy' 'Financial & Fiscal' 'General' 'Other' 'Information & Training' 'Regulation & Standards' 'Market-based instruments' 'Supportive Actions' 'Research' 'Standards'	'Transport', 'Buildings', 'Agriculture', 'Energy sector', ‘Societal’, 'Electricity', 'Heating and cooling', 'Industry', 'Fuels'	‘Broad Technological Focus’ 'Electricity' 'Waste incineration' 'PtX' 'Heat pumps' 'Renovation' 'Storage' 'Energy efficiency' 'Infrastructure' 'District heating' 'Transmission & distribution' 'Boilers' 'CHP' 'Distribution’ 'Power plants’ 'CCU’ 'Excess heat' 'CCS' 'Space Heating' 'Thermal energy'	'Fuels' 'Nuclear' 'Natural gas' 'Oil' 'Coal' 'Renewables' 'Geothermal' 'Photovoltaics' 'Wind' 'Solar thermal' 'Wave power' 'Hydro' 'Biomass' 'Biofuels' 'Solid biomass' 'Biogas' 'Bioenergy' 'Liquid biomass'

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ISSN (online): 2446-1628
ISBN (online): 978-87-7210-989-3

AALBORG UNIVERSITY PRESS