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Case study of Greater Copenhagen District Heating Network

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DOI (link to publication from Publisher):
10.54337/aau443829316

Publication date:
2021

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

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BY
MAËLLE CAUSSARIEU

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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Dissertation submitted: 19th April 2021

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PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Planning

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-933-6

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 studies the ongoing energy transition of the Greater Copenhagen district heating (DH) network. Energy system transitions are, within the social sciences, often considered as a matter of large-scale technological innovation and diffusion, and little attention is given to the people engaged in these endeavors. This thesis provides a new perspective on energy system transitions. Based on insights from Science and Technology Studies (STS), it follows the ongoing work of the energy practitioners and investigates three transitioning sites within the Greater Copenhagen DH system.

As a backdrop for the analysis, this thesis reviews the three strands of literature that stand out in energy transition studies: engineering, economics, and the more sociologically informed field of 'Transition Studies'. The review highlights their key approaches, studies, and debates and identifies the main analytical and empirical gaps, which then paves the way for the theoretical and methodological contributions informing this thesis.

Drawing on a relational approach, the Sociology of Translation and Sociology of Markets, the analyzes follow the actions as they unfold, drawing out the messiness of transitioning processes. Particular emphasis is given to the analytical and calculative tools – the material devices – that practitioners use to help make sense of the transition processes.

The thesis explores energy system transitions in three sites, namely, the Greater Copenhagen socio-technical network, the establishment of the first regional Thermal Energy Storage (TES), and Albertslund DH utility's work of achieving a low-temperature heat supply. The analysis of developments in Greater Copenhagen shows how a number of energy transitions have and are occurring. It follows the work of the practitioners and the plurality of material devices they mobilize in the course of making the transitions. The analysis shows that as a result of the numerous associations between the practitioners and devices, the DH practitioners manage to simultaneously maintain and transition the regional DH system.

The second analysis follows the 5-year implementation process of the first regional TES. It illuminates the work conducted by the practitioners to make new objects in pre-established and complex socio-technical networks knowable and, thus, actionable. The analysis shows that the devices that equip the actors enable new kinds of coordination work and allow the actors to cope with uncertainties. In the third analysis, I investigate the district heating utility's enactment of energy transition in Albertslund, a small municipality in the Greater Copenhagen region. This analysis reveals that the work of achieving a low-carbon future entails mundane challenging work to create new devices and associations between a wide array of human and non-human elements and, thus, does not follow a pre-defined technological path. The

analysis follows the practitioners' efforts to make heat(s) visible to customers in new ways and enable new economic flows to circulate, as well as the means through which the DH utility intends to shift its boundaries from within its DH network, thereby enabling new capacity for action.

The empirical results are discussed in light of the Transition Studies approach and in terms of their transition potential. Further I discuss the 'habilitative vs. prosthetic' role that material devices can have. I argue that energy system transitions are more discrete than though in Transition Studies. The work of transitioning is not about large-scale technology diffusion nor struggles between actors who are *de facto* for or against particular technologies. Instead, energy transitions are considered as outcomes of the everyday work of practitioners who are simultaneously maintaining and transitioning their energy systems. In doing so, the practitioners are assisted by a multiplicity of devices which, each in their own way, assist them in knowing and acting in their worlds. The DH practitioners are acting from their situated perspectives, trying to grip their world that is constantly evolving. In conclusion, energy system transitions are considered as situated and fragile achievements, constantly in the making. They are, therefore, neither accidental nor pre-determined, but continuously emerging.

MAËLLE CAUSSARIEU is a researcher in the Design for Sustainability Group, Planning Department, at Aalborg University, Copenhagen.

DANSK RESUME

Afhandlingen undersøger den igangværende energimæssige omstilling i det Storkøbenhavns fjernvarmesystem udfra et socio-teknisk perspektiv. Som optakt til de empiriske analyser heraf, gennemgår afhandlingen centrale dele af den ingeniørfaglige, økonomiske og mere sociologisk informerede litteratur, der beskæftiger sig med omstilling af energisystemer. Gennemgangen fremhæver de vigtigste tilgange, undersøgelsesresultater og debatter, og identificerer de vigtigste analytiske og empiriske 'huller'.

Med udgangspunkt i en relationel tilgang, der betegnes 'the Sociology of Translation and Sociology of Markets', undersøges hvordan fagprofessionalle inden for energifeltet arbejder med at omstille – decarbonisere – fjernevarmesystemet. Den valgte tilgang gør det muligt at følge de forskellige aktørers handlinger imens de udfolder sig. Det bliver således muligt at følge de mundane handlinger som bidrager til fjernvarmesystemets omstilling. Særlig opmærksomhed rettes mod de forskellige beregningsmetoder og artefakter, som fagfolkene benytter sig til at definere og afgrænse de energimæssige udfordringer, da disse både repræsentere og præsentere hvorledes omstillingssprocesserne kan finde sted. Disse beregningsmetoder og artefakterne – som sammenfattende beskrives på engelsk som 'material devices' – er valgt som en analytisk indgang i afhandlingen.

Fjernvarmesystemets omstilling undersøges i tre tilfælde. Undersøgelserne er baseret på dokumentanalyse og analyse af interviews med fagfolk i fjernvarmebranchen. De tre analyser drejer sig om udviklingen i Storkøbenhavn, udviklingen i og anvendelsen af en bestemt lagerteknologi samt hvordan overgangen til er såkaldt 4. generationsanlæg sker i en af Københavns omegnskommuner. I alle tre tilfælde følges de fjernvarme professionelle brug af forskellige 'material devices' i omstillingsarbejdet. Førstnævnte analyse viser, hvorledes de fagprofessionelle arbejder med at vedligeholde fjernvarmenettets daglige funktion, samtidig med at de transformerer det til en fremtidssikret energiforsyning. I den anden analyse følges en fem år lang implementeringsproces for det første regionale varmelager i Storkøbenhavn. Analysen viser, hvad det kræver af fagfolk når nye 'objekter' skal gøres synlige og håndterbart. Det viser, at 'the material devices' muliggøre nye former for koordinationsarbejde og at de assisterer fagfolk i deres ageren i situationer kendetegnet af usikkerhed. Den tredje analyse beskæftiger sig med Albertslund Forsynings strategi for at transformer deres fjernvarmenet fra et traditionelt forsyningssystem til et såkaldt '4. generationsfjernvarmenet'. Analysen viser, at arbejdet med at opnå denne omstilling ligger langt fra mange videnskabelige forestillinger, idet den fremhæver det almindelige og udfordrende hverdagsarbejde i at synliggøre varmeforbrug for kommunens beboer og for at motivere dem til at skifte deres varmeforbrugsvaner.

Afhandlingens resultater diskuteres i relation til indsigter fra transitionslitteraturen, og tilbyder en anden fortolkning af energisystemomstillinger. Fremfor at betragte energisystemomstilling som (primært) et spørgsmål om spredning af teknologi eller som en kamp mellem aktører, der enten er for eller imod indførelsen af bestemte teknologier og dermed omstilling af systemet, tilbyder afhandlingen et blik på det praktiske hverdagsarbejde som fagfolk bedriver og som samtidig bidrager til at vedligeholde og transformere energisystemet. De fagprofessionelle benytter sig af et stort antal 'devices', der hver på deres måde, hjælper dem til at kende og handle i deres (situerede) socio-tekniske netværk. Fjernvarmefolk handler ud fra og i forhold til den kontekst, som de befinder sig i.

ACKNOWLEDGEMENTS

Those who are familiar with the Sociology of Translation are acquainted with the idea that an action is necessarily distributed. The fundamental idea is that an achievement such as, let's say, completing a Ph.D. thesis, is not the result of a Ph.D. student alone. Rather, the success of the achievement extends to a network of other actors who, in one way or another, have contributed to the thesis completion. I want to seize this occasion to thank the ones whom, too, have participated in making this dissertation meeting the finish line.

The first 'thank you' goes to my supervisor, Susse Georg. In French we have the word "bienveillance", to which I haven't find a good English counterpart. Bienveillance could be literary transcribed as "good watchfulness". It carries an idea of kindness, attentiveness and support. This is how Susse has been for me during these three years: kind, attentive, and supporting. This PhD thesis would have never come together without your warm encouragement, generosity, wisdom and constructive feedbacks. It means a lot, and I am very grateful (and feel also quite lucky) to have had you as a supervisor.

A second thanks goes to my co-supervisor, Peter Karnøe. Thank you for introducing me to a school of thought, which, despite my confusions, you have never despaired clarifying. For your metaphors, curiosity, thoughtful advices and stimulating discussions along the way, thank you.

Another special 'thank you' goes to the Valuation Group of Aalborg University. Inge Røpke, Jens Iuel-Stissing and Ask Greve among others, thank you for the inspiring discussions, for generously taking your time to hear and support progress along the way, as well as for the shared laughter. This research environment has not only been stimulating, but also truly cheerful. My gratitude also extends to the broader Valuation and Sociology of Markets scholars met along the way, which, to my greatest pleasure, turned out to be a professional family of French and Danish academics.

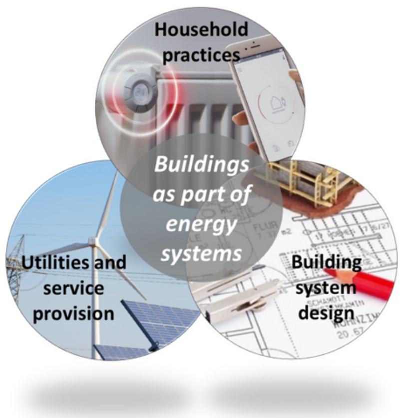
And to all the people that I have met during the field work, thank you! It has been a pleasure. Never would I have imagined becoming, one day, so interested in district heating. For your enthusiasm, your time, for what you shared, and offered, thank you.

And last, but not least, this Ph.D. would not have come along without the good company that I had along the way. Thank you for being the greatest friends, for your presence, for the discussions, support, and, undeniably, for the countless laughter. To Nis, Charlotte, Suzanne, Leïla, and my mother, among many others, thank you.

And to Lotta, always in my heart.

This Ph.D. thesis is part of the interdisciplinary research project InterHUB: Intermittent energy - Integrating Households, Utilities and Buildings.

The purpose of the project is to develop insights as to the challenges of integrating buildings and households in a flexible energy system. It focuses on three specific dimensions: building systems design, household practices, and energy provision.



This Ph.D. thesis addresses the latter dimension, namely, energy provision. The aim of the project was to investigate how district heating utilities' roles are challenged as a result of the buildings' integration into the energy system, and to explore the ways in which utilities develop new business models and make valuable new services to their customers. This Ph.D. project has however taken a slightly different path and, rather, focuses on the ways in which district heating utilities achieve energy transitions.

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CHAPTER 1. INTRODUCTION

Energy system transitions are a central key to mitigating climate change – one of society's most pressing concerns. Societies' surging energy consumption and dependency has increased the concentration of greenhouse gases in the atmosphere to such an extent that climate change is widely recognized as being underway (United Nations 1992; IPCC 2018). Energy provision and use is double edged: on the one hand, energy is essential for modern societies' activities, but on the other, it is also contributing to one of the biggest threats to society's daily and future activities (Rockström et al. 2009; Malm 2016).

The issue of energy transition has been on the policy agenda for decades. For example, the first consolidated international response to the climate issue, the Kyoto Protocol (signed in 1998 by 192 parties) established an international commitment to "*develop[ing] and increas[ing] use of, new and renewable forms of energy*" (United Nations 1998, 2). With the signing of the Paris Agreement fifteen years later, even more countries pledged to reduce energy-related carbon dioxide (CO_2) emissions by scaling up renewable energy and reducing energy intensive activities (United Nations 2015). However, energy system transitions and their effects on greenhouse gases emissions still remain strangely abstract and intangible, as witnessed by the worldwide steady increase in energy-related CO_2 levels in 2018 (IEA 2019).

Despite the longstanding interest in energy system transitions, it appears that they are occurring at a very slow pace. Why is this the case? If "energy system transitions" are being so widely debated in policy, business and academic circles (Köhler et al. 2019), why are so few changes materializing?

Currently, much of the research on energy transitions is focusing on the technological aspects of these necessary transformations. Experts have been modelling Smart Electrical Grids, 4th Generation District Heating systems, Smart Buildings, and many other 'smart' technologies for years (Marszal et al. 2011; Lund et al. 2010; Mathiesen et al. 2013). However, despite the promise of these technologies in terms of limiting carbon emissions, expectations have still not been met, or at least not to the extent expected (Rau, Toker, and Howard 2010; McLaren 2020). Grids, district heating systems, and buildings (among many other forms of energy technology) are not 'just turned' into low-carbon technologies: buildings cannot 'just' be replaced by 'Green Buildings', electrical grids cannot 'just' be replaced by 'Smart Grids', and heavy fuels cannot 'just' be replaced by carbon-free combustibles. Energy infrastructures can not just be supplanted by 'smart' and 'effective' interconnected systems thanks to technological innovations with the wave of a magic wand (Geels 2002; Unruh 2000).

Rather, energy systems are complicated infrastructures that are fundamentally interlinked with institutional, organizational, political and economic factors. These interconnections generate positive institutional and economic feedback loops; economies of scales, institutional co-evolutions and market dynamics support the existing energy infrastructures and tend to exclude (sustainable) alternative infrastructure (Unruh 2000; Geels 2002). Consequently, reinforcing mechanisms perpetuate the energy systems, which become obdurate and difficult to transform (Geels et al. 2016; Sovacool 2016).

Furthermore, energy systems are deeply influenced by the way in which they are created, operated and maintained by practitioners. The engineers and system managers responsible for the infrastructures base their decisions on persistent mechanisms that are influenced by, and feed into, political and economic incentive structures (Hughes 1987). Thus, as transitions are bounded by the ways in which energy practitioners operate and work with the infrastructures at hand, energy system transformations are not a simple matter of optimization and increased efficiency (Hughes 1987; Unruh 2000; Kemp and Loorbach 2003).

Furthermore, due to their expertise, knowledge of the field, position and established relationships with energy customers, energy practitioners are central actors in terms of transforming the energy supply towards a low-carbon future (Sperling, Hvelplund, and Mathiesen 2011; Helms 2016). They are the ones that have to plan, invest and implement new technologies while having to abide by regulations regarding energy provision. Energy practitioners are, thus, at the heart of energy transitions, and are responsible for a paradoxical task: they need to ensure the daily energy provision, and simultaneously radically transform it towards a low-carbon future (Unruh 2000; Birch 2016; Bulkeley, Castán Broto, and Maassen 2014).

However, this task is seldom straightforward as it is subject to considerable uncertainty, and the practitioners have to cope with a number of issues; they need to negotiate, evaluate technological potential, assess uncertain future outlooks, and enact an array of laws and regulations (Meadowcroft 2012; Jensen et al. 2015; Quitzau et al. 2013). Practitioners have to engage in decision-making activities without having access to fully stable and certain information about the present (and future) state of the world in which the energy systems exist (Quitzau et al. 2013; Jensen et al. 2015).

However, only limited insight exists as to the ways in which the energy practitioners can (re)assemble energy systems towards a low-carbon future in situations of high uncertainty. How do they manage the tensions, ambiguities, and struggles that they face when engaging with infrastructural transformations such as energy system transitions? These are some of the questions that this Ph.D. thesis aims to answer.

Practitioners are, however, not ‘naked’ actors in the field; they are not ‘out there’ unequipped, deciding what decisions to take and what technology to implement as the wind blows. Rather, they are assisted by specific tools and equipment that support their tasks; modelling software, business models, energy outlooks, etc.; these are all devices which enable the practitioners to calculate and, therefore, act despite substantial uncertainty. These tools and equipment (or ‘material devices’) have a salient role to play in navigating (and achieving) energy transitions (Callon 1998; Muniesa et al. 2007).

Nevertheless, these devices do not ‘just’ assist the practitioners in their work of coping with uncertainty in transitioning processes; they also co-construct the worlds in which they exist (Doganova and Eyquem-Renault 2009; Garcia-Parpet 2007; MacKenzie 2003). The tools and equipment (or ‘material devices’) are not inert. They do not just passively inform the actors. Instead, they make specific aspects of reality visible and, thus, actionable. For example, by making either the carbon emissions or the heat prices of a given energy production visible (and knowable), two measuring tools can provide two different representations of the world, which, in turn, allows the actors to undertake distinctive actions. In other words, the material devices that equip the practitioners enact particular forms of reality and, consequently, they can promote certain futures over others (Callon 1998; Çalişkan and Callon 2009).

Against this backdrop, the thesis follows the actions, ambiguities, tensions, and devices that energy practitioners may mobilize in transitioning to a low-carbon energy future. Studying the work involved in energy system transition is, however, specific to a time and place (Czarniawska 2004). Accordingly, the thesis focuses on the transitioning of one energy system in one place, namely, Greater Copenhagen district heating system.

Inquiring about district heating system transitions in Denmark

Denmark has been heralded as a pioneer in energy transition (Gerdes 2013; *The Guardian* 2015). Although the successful introduction of wind power is the most well-known sustainable energy achievement, Denmark is also recognized for its widespread use of district heating (DH) and its potential for sustainability (Lund et al. 2010).

While gas, electricity, and fuels can be produced/extracted in one place and consumed in another, DH is a geographically bounded form of energy; the heat can only be produced and consumed locally (S. Frederiksen and Werner 2013). The heat, which is used for space heating and domestic hot water, is typically generated from central production units and then distributed in a closed loop to buildings through a network of underground pipes, where the water is cooled down, and then sent back again to the production sites. Accordingly, DH systems are highly dependent on the urban fabric, pipe layout, specific heat production technologies, (e.g., CHP plants, heat pumps, industrial surplus heat), and local heat demand (S. Frederiksen and Werner 2013).

Today, heating represents more than 80% of the total energy consumption of Danish households (DEA 2019, 27), and DH is still based on a combination of energy resources such as coal and imported biomass (DEA 2018). However, DH systems have the potential to integrate large amounts of electricity generated by wind power. District heating is considered an important means of decarbonizing the energy system and as having significant potential in terms of ensuring a low-carbon future (Connolly et al. 2013; Roberts and Geels 2019; Lygnerud 2019).

Although there are numerous studies about the technological aspects of decarbonizing the DH sector (see, for example, Connolly et al. (2014); Hast et al. (2017); Andersen and Østergaard (2018)), to my knowledge, no socio-technical studies have inquired into the work of the DH practitioners and their attempts to reduce carbon emissions. In order to address this research gap, I propose answering the following main research question:

> How can district heating system transitions be enacted by practitioners, and what roles do material devices play in these processes?

As noted above, energy practitioners have the paradoxical task of simultaneously transitioning energy systems while ensuring their maintenance and security of supply. In doing so, they have to cope with significant uncertainties, work and coordinate actions in new ways, and mobilize or create new material devices to assist the tasks at hand. In order to answer the main research question, I also examine the following three sub-questions:

- What work is required to simultaneously maintain and transition DH systems, and how do specific concerns influence the transitioning processes?
- How do practitioners cope with uncertainties and coordinate actions when preparing low-carbon technological futures?
- What role does the creation of new material devices play in assembling a low-carbon DH system transition?

The approach taken

Drawing on a relational approach (Latour 2005), which asserts that both humans and non-humans actors have agency and the capacity to affect other actors, energy system transition is considered as an effect of site-specific associations between heterogeneous actors. These associations are seldom stable but instead they are considered to be constantly evolving, i.e., *in the making*, and to constitute precarious socio-technical networks (Callon 1986a). Viewed from this perspective, energy system transition is a precarious achievement, which can be brought about by practitioners and the tools (or ‘material devices’) that assist them in defining and assembling (situated) energy transitions.

Furthermore, DH systems are dependent on the urban fabric (the age of the buildings and heating systems, the grid layout, etc.), the number (and type) of customers, the different types of technologies (diverse production units, distribution components, meters, etc.), etc. Hence, DH system transitions can be enacted in a plurality of ways. For example, ‘transitioning’ for a large heat producer may be enacted by a shift in fuel from coal to biomass, which entails considerable investment in production units, whereas for a municipal heat planner, it may be enacted by establishing a new heat pump or by attempting to reconfigure the customers’ heat practices. Therefore, DH transitions are place-based (or ‘situated’) enactments; they are specific to certain actors in time and place.

Accordingly, this thesis investigates developments in a particular site, namely, Greater Copenhagen DH infrastructure. With nearly 200km of underground transmission pipes and servicing approximately ½ million households, Greater Copenhagen has one of the largest district heating systems in Europe, and the municipality is aiming for becoming CO_2 neutral by 2025 (Werner 2017; CTR, HOFOR, and VEKS 2020). The DH practitioners are, thus, responsible for transitioning the large-scale energy system towards carbon neutrality, while ensuring the daily heat supply. But what does transitioning such a large-scale energy system with its diversity of heat production units, spread DH layout, and varied urban fabric entail?

To understand the background where the actors come from and where the actions unfold (yet without invoking ‘context’ as an explanation), the relational perspective calls for following the actors and tracing back some of their past associations (Asdal 2012). Because “*the past engages the future*” (Callon 1991, 151), the thesis starts by tracing back some of the (recent) developments in this large-scale infrastructure. This then sets the scene for delving into the messiness of the ongoing transitioning processes in Greater Copenhagen’s DH (socio-technical) network. This forms the foundation for following, and understanding, how different material devices have assisted, and are assisting, the practitioners in their attempt to make a low-carbon future known and, therefore, actionable.

Structure of the thesis

The remainder of this thesis is structured as follows:

Chapter 2 provides a review of the literature concerning energy system transitions. It focuses on the three main bodies of literature, namely, engineering, economics, and Transition Studies. Most of what has been written about DH comes from engineering, which emphasizes technical analyzes of, e.g., the introduction and use of specific technologies such as solar heating or seasonal storage, modelling system optimization and analyzing how DH systems can be 100% based on renewable energy sources through system optimization and technology implementation. From the realm of economics, studies have investigated the challenges faced by DH utilities with regard to their business model as a result of the integration of fluctuating energy sources such as wind. These studies focus on the business model components and on how they could be remodeled by power utilities so as to create value and enable the implementation of new technology. Drawing on managerial and economic theories, this literature focuses on the utilities as economic entities but does not consider the socio-technical entanglements of DH.

Lastly, the Transition Studies literature, which draws on evolutionary economics, studies the mechanisms through which (energy) infrastructures are established and sustained, and the ways in which technological alternatives are excluded. Much of this literature takes technology diffusion as their unit of analysis and does not consider the processes (or the work involved in) transitioning. Transition Studies scholars consider actors in the field as being either for or against technological change, and they pay little or no attention to the material devices that equip the customers in their work of assembling transitions.

The literature review then paves the way for introducing the theoretical approach I take, which is presented in Chapter 3. As noted above, this thesis takes a relational approach. Grounded in the Sociology of Translation and Sociology of Markets, the approach enables a new way of conceptualizing energy system transitions. Instead of considering energy transition as a matter of technology diffusion, this theoretical approach investigates transitions as phenomena that are always in the making. It leaves open the categorization of actors, resources and technology. It directs one to closely follow the ongoing uncertainties, struggles, and actions, unfolding in the (place-based, or 'situated') socio-technical networks of district heating.

This then leads to the methodological considerations that inform this thesis, which are presented in Chapter 4. The theoretical approach implies following the actants *in media res* and attending to the particular heterogeneous elements (the pipes, material devices, practitioners, etc.) that compose the (situated) energy transitions. The chapter clarifies the reasons why a case study is appropriate for studying ongoing phenomena, and how, through interviews and retrieved documents, this thesis explores the practitioners, their material devices, their concerns, the uncertainties and their courses of action.

Chapter 5 presents an analysis of transitions in the Greater Copenhagen district heating socio-technical network from the 1970s until today. Paying particular attention to the on-going transformations, the chapter follows the practitioners' efforts to maintain the security of supply at a low price while adapting to a plurality of changes. The chapter reveals the diversity of material devices mobilized by the actors in their efforts to maintain the stability of the system and shows the attempts made by the practitioners to re-assemble their worlds. The chapter also reveals the importance of social ties and practitioners' willingness to be part of a common future for transition work.

Chapter 6 studies the implementation of the first regional Thermal Energy Storage in Greater Copenhagen. Based on material collected over a period of 5 years, the chapter reveals the vivid uncertainties and issues met by regional district heating actors in their efforts to make a low-carbon future knowable and actionable. The chapter shows that calculations and business models are particularly important and problematic in the early stages of the implementation process (in 2017-18), and that, towards the end of the implementation process (in 2019), they become secondary and serve as a backdrop for the negotiations.

Chapter 7 investigates the transition of a municipal district heating system from a 'traditional' to a low carbon '4th Generation District Heating' grid. It follows the practitioners' efforts to assemble a particular technological future through mobilizing and creating new material devices. The chapter shows that the situated and particular circumstances have implications as to how the municipality enacts "energy transition" and "sustainability".

Chapter 8 discusses how these findings relate to the extant literature on energy system transitions. It discusses the advantages of adopting a relational, rather than a structural, perspective when investigating energy system transitions. The chapter argues that this reveals the diversity of transitioning processes and illustrates that energy system transitions entail much more than technology diffusion. It further discusses the different roles that the material devices play in the three studied instances. Lastly, I discuss the "transitioning potential" (Labussière and Nadaï 2018) of district heating and how the devices used by energy practitioners serve as a mean of "habilitation" and "prostheses" (Callon 2008). Discussing these two agendas contributes to the further conceptualization of energy system transitions and the ways in which material devices participate in these.

Lastly, Chapter 9 draws some conclusions based on the findings of this thesis. It highlights the specific contributions to the literature, discusses the limitations of the study, and suggests directions for future research.

CHAPTER 2. LITERATURE REVIEW

There is a burgeoning literature on climate change and the need for energy (system) transitions. A quick search on Google Scholar and in academic databases reveals two things: first, even though energy transitions is a widely addressed topic, there are three strands of literature that stand out in terms of the number of publications: engineering, economics, and the more sociologically informed field of 'transition studies'. Second, much attention has been given to energy transitions as the increased use of renewable energy sources and the technical and economic implications this has, notably, for the electricity system. Much less attention has been given to district heating transitions.

As a means for setting the stage for what is to come, this chapter briefly presents how the issue of district heating transitions is addressed within each of these domains. Given that much of the work on district heating transitions is found in the engineering literature, e.g., in (high impact) journals such *Applied Energy*, *Energy* and *Energy Conversion and Management*, the chapter opens with a presentation of the key insights from this literature. The following section focuses on the economic analyses of district heating transitions. Much of this research can be found in journals such as *Utility Policy* and *Energy Policy,* which are at the nexus of the engineering and economics disciplines. This research 'goes beyond' the technical aspects of district heating transitions and considers some of the economic and organizational factors influencing the system's innovations, notably the need for business model innovation (BMI).

Lastly, the chapter focuses on 'transition studies' – an approach grounded in the sociology of technology and which draws on evolutionary economics (Geels, 2002). These studies, published in interdisciplinary journals such as *Energy Research and Social Science*, *Journal of Cleaner Production*, and dedicated journals such as *Environmental Innovation & Societal Transitions*, are widely recognized for their contributions to understanding system transitions, specifically within transport and energy systems (Köhler et al. 2019). Unlike much of the engineering and economic literature, which (respectively) emphasizes the technical and economic aspects of transition, transitions studies seek to address the multidimensionality of energy transitions.

Accordingly, I seek to explore what this strand of literature offers when it comes to understanding district heating transitions because there are, to my knowledge, only a few studies focusing on district heating transitions (Carrosio and Scotti 2019; Roberts and Geels 2019). Although it is difficult to ascertain, this apparent lack of interest in district heating transitions may be attributed to the geographically limited expansion of DH infrastructure, which is predominantly found in the Nordic countries, China and Russia (Werner 2017).

Altogether, this chapter gives a picture of the key approaches, studies, and debates concerning DH transitions. The review concludes by discussing the main gaps, both theoretical and analytical, which paves the way for the theoretical considerations informing this thesis.

2.1. ENGINEERS AND DISTRICT HEATING TRANSITIONS

District heating is an engineering field with particular contributions from Denmark, Sweden, Finland, and Germany, presumably because these are the countries in the world with highest penetration and longest history with district heating (Werner 2017). The literature describes district heating as the technical understanding of "*us[ing] local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place*" (Werner 2017, 618). Typically, excess heat sources are Combined Heat and Power (CHP) plants, which produce heat as a by-product of electricity production, but excess heat can also come from industrial processes and waste incineration plants. These systems are considered in the engineering literature as efficient and as having low costs and a low environmental impact in dense areas such as cities. Nevertheless, district heating systems are limited to a few geographical areas; they are present in some of the largest Russian and Chinese cities (e.g., Moscow, St. Petersburg, Beijing), and in eastern and northern Europe (Kiev, Berlin, Stockholm, and Copenhagen, among others) (Werner 2017).

It is now widely recognized that combating climate change calls for the increased use of fluctuating energy resources, such as wind power, in order to acheive low-carbon energy systems (Brum et al. 2015; Mathiesen et al. 2015). However, intermittent production provokes issues of grid frequencies and forced electricity exports in times of excess generation, and supply issues in times of insufficient generation. In other words, as the electrical grid can not be based on the traditional norm *supply-follows-demand* (Karnøe 2013; Connolly et al. 2012), discrepancies between the available and demanded electricity are generated, thereby challenging the stabilized operation of the electrical system. Instead, demand must follow production-supply, which means that new systems must be flexible (*ibid.*).

To tackle these issues, engineers have identified the need for system optimization through "smart" sector coupling such as the electrification of transport, heat, and cooling (Mathiesen et al. 2013). By using conversion technologies such as electrical batteries for vehicles, heat pumps for cooling and heating networks, it may be possible to flexibly integrate a large amount of renewable energy without threatening the stability of the grid or the security of supply (IDA 2009; Sayegh et al. 2017).

However, most of the research on electrical grid and energy system focuses on what can be done within specific parts of the energy system (S. Frederiksen and Werner 2013), and only a few researchers have focused on the energy system as a whole

(Kondziella and Bruckner 2016). Among those that take a system view are Danish engineers, who have shown, among others, that Denmark can rely on 100% renewable energy sources (IDA 2009).

These researchers attempt to avoid sub-optimization within the sub-sectors and, therefore, aim to identify synergies within them. They have proposed the concept of "Smart Energy System", which is defined in the following:

> 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 (Lund 2014, 11).

By using modelling software simulating such cross-sectoral national energy systems (i.e., including electricity, heating, cooling, transport and industry sectors), researchers have attempted to identify national energy strategies with limited environmental and economic impacts (Connolly et al. 2010). The Danish engineers have designed desirable technological energy futures and modeled the multiple pathways that can lead to the projections. They propose documenting (and creating awareness about) the fact that 100% renewable energy systems are achievable. They include institutional and political factors (such as taxes and regulations), and conclude by providing specific policy recommendations that they consider support energy transitions. Although their analyses do not include practitioners, the Danish scholars conclude that established actors (e.g., institutions, power companies) have the tendency to be against radical technological change and that offering an alternative perception of reality can promote energy transitions (Lund 2014).

The notion of 'smart energy systems' has received international recognition (Sayegh et al. 2017). In this notion, engineers have argued for the need to transform district heating grids from 'traditional' to "4^{th} Generation" systems, which are defined in the following:

> The 4th Generation District Heating (4GDH) system is (...) a coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems (Lund et al. 2014, 10).

This concept has established a new scientific engineering vision of district heating and has demonstrated its technological potential in realizing low-carbon futures (IDA 2015; Connolly et al. 2013). Energy engineers have modeled different 4GDH infrastructures (Connolly et al. 2014), the role of various technologies such as heat pumps (Gaur, Fitiwi, and Curtis 2021), heat storages (Romanchenko et al. 2018), and

Combined Heat and Power (CHP) (Levihn 2017) in 4GDH futures. These studies have gradually established a common and shared understanding of the technical dimensions of future district heating systems, but they have also acknowledged the need for other academic disciplines to investigate the realization of these projections:

> 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 of these (Lund et al. 2018, 614).

In documenting the technological possibilities, these analyzes have thus also identified the need for contributions from other disciplines that investigate the social, organizational, regulatory, and business dimensions of district heating transitions. The following section presents the latter aspect with contributions from Business Model Innovation researchers.

2.2. BUSINESS MODEL INNOVATION RESEARCHERS, CHALLENGING UTILITIES' BUSINESS AS USUAL

Much of the economic literature on energy transitions focuses on issues relating to the creation and competitiveness of energy markets (Silvast 2017). In light of fairly recent developments within the electricity sector (i.e., debundling and deregulation in the US and soon after in Europe), it is not surprising that much of the economics informed literature focuses primarily on this sector and less on district heating. However, as Lund et al. (2018) assert that technology is not the problem, but instead that the implementation of 4GDH by DH utility is limited by economic and regulatory factors, economic research is relevant for district heating transitions (Leoni, Geyer, and Schmidt 2020).

A salient topic in this literature is the challenges power utilities face with regard to their business models and service propositions as a result of the increasing integration of decentralized and fluctuating energy resources (Richter 2012; Lehr 2013; Helms 2016). Increased attention is being given to analyzing how power supply companies can/are remodeling their business models in response to the integration of renewables; often cast as Business Model Innovation (BMI) (Helms, 2016). BMI studies draw on managerial and economic theories to understand how different business components can be revised to achieve successful technology implementation. According to the theory, the establishment of the right business model will lead to successful business implementation and, hence, will enable power utilities to achieve sector coupling and thereby integrate more renewable energy sources, as argued by Lund (2014) (Rosenbloom and Spencer 1996; Chesbrough 2010).

District heating utilities face similar challenges as electrical utilities because the increased integration of renewables also affects their operation. However, this has not received as much attention in international studies as the challenges faced by electrical utilities (Leoni, Geyer, and Schmidt 2020). In light of these similarities and the dearth of BMI studies on DH utilities, I would like to also introduce a few studies on BMI within the power sector. Helms (2016), who is one of the most cited authors on BMI in power utilities, opens his study of how electrical power companies can transform their business models in the following way:

> [S]cholars and managers agree that utilities need to fundamentally innovate their business models (BMs) to overcome their role as commodity suppliers and become service providers for comprehensive energy solutions (Helms 2016, 94).

Helms (2016) examines the possibility of electrical utilities transforming their business model from product- to service-oriented. The study identifies value creation, asset transformation, and managerial enhancement as key elements of new business models for managing energy transitions while simultaneously ensuring energy delivery. Helms (2016) asserts that overlooking the geographical and contextual elements may result in addressing business models' inherent complexity of their success/failure inadequately. The importance of geography and context is clearly also an issue when it comes to district heating as heat and service provision is inextricably intertwined with the urban fabric, i.e., the age and 'shape' of the production, transmission and distribution infrastructure as well as the buildings to which heat is provided (S. Frederiksen and Werner 2013).

More recently, Burger and Luke (2017) conducted a review of 144 new business models of electrical power companies and found that both 'incumbent' power utilities and new energy communities are developing new business models. After identifying five archetypal business models, the scholars note that these, "*appear to be driven more by regulatory and policy factors than by technological factors*" (p.245). Burger and Luke (*ibid.*) suggest that future research should focus on finding the, "*optimal design of regulations and policies*" (p.246) to avoid policy dependence and conclude that their study was, "*a first step"* (p.246) towards understanding the factors influencing power utilities BMI. Other scholars studying electricity power utility have arrived at the similar conclusion that technology is not a barrier to the integration of renewable energy sources but that instead, business models must be remodeled to drive the low-carbon energy transitions (Szatow, Quezada, and Lilley 2012; Bolton and Hannon 2016; Betsill and Stevis 2016; Burger and Luke 2017; Mazur et al. 2019). Concludingly, these studies contribute to understanding how power utilities can adapt and foster energy transitions through the establishment of new business models.

Even though much of the BMI informed literature focuses on developments within the power sector, there are a few studies of how district heating utilities are adapting to changes in their business environment as more and more renewables are introduced into the energy system. Lygnerud (2019) investigates how district heating utilities could remodel their business model for transitioning to a 4GDH.

Lygnerud (2019) studies six "frontrunner" utilities, which claim to have implemented 4GDH networks, at least partly. The study includes an analysis of the business canvas of each of the utilities, taking into considerations elements such as customer value, type (large building owner vs. individuals), channels (invoices) and the key activities, resources and partnerships on the DH side. The study finds that these district heating utilities are still at the technical test phase, that is, they have recently added new energy technologies (e.g., heat pumps, geothermal) and new skillsets (i.e., on the "*technical operation of the low temperature systems*" (p.12)) amongst staff, but have not adjusted their business models accordingly. Therefore, the author suggests that, to remain competitive and efficient, these district heating utilities also need to develop the business side. Lygnerud concludes as follows:

> None of the cases studied expressed a strategy for materializing both technical and business value of the technology shift. (...) It is concluded that there is an unexplored potential for district heating companies to capitalize on the low temperature technological shift (Lygnerud 2019, 16).

Although the study notes that the findings cannot be generalized to all DH utilities, the author suggests that further research should nonetheless investigate how the technical and business values of the 4GDH can be achieved.

Similar to Lygnerud (2019), Leoni, Geyer, and Schmidt (2020) review "*success stories"* of DH companies in the shift from traditional to 4GDH systems. The review of the "*best-practice examples*" (p.2) is then used to define the most appropriate business model DH utilities could use for implementing 4GDH systems. The scholars intend to overcome technical, economic and instutionals barriers to 4GDH by, "*elaborate[ing] business models promoting a substantial temperature reduction in existing DH systems and enabling the transition towards the 4GDH*" (p.8). In their study of Austrian district heating utilities, they find that:

> [M]ost of the Austrian DH utilities currently deal [sic] with major market challenges. A significant temperature reduction has then become an important target to increase in competitiveness, besides to decarbonize the heat sector and enable the transition towards the 4GDH (Leoni, Geyer, and Schmidt 2020, 2).

The authors conclude that, in order to make the transition economically viable, DH utilities should incentivize their tariffs to motivate their customers to reduce their heat consumption, establish energy saving contracts, and establish strategic partnerships with other utilities or with ICT firms. Nonetheless, the scholars note that, *"the proposed ideas need to be verified on the field*" because their success remains "*case-specific*" (Leoni, Geyer, and Schmidt 2020, 8).

However, as Lygnerud (2019, 4) notes, there are only, *"a few studies on DH business modelling*". Insightful as these studies may be with regard to the changing operational opportunities for DH, which moves the analyzes closer to the actors involved, they appear to treat business models as mere representations of reality through which technological and business potential can be revealed. The authors do not consider business models as 'market devices' (Muniesa et al. 2007), i.e., as "*intermediaries that circulate in the techno-economic networks of innovation*" (Doganova and Eyquem-Renault 2009, 1559). Authors who support this understanding, to which we return in the next chapter, argue that business models are socio-technical constructions that enable market exploration and new products to be brought into being.

2.3. TRANSITIONS STUDIES – APPROACHES AND DEBATES

Social science scholars assert that energy transitions concern more than just technological and economic issues (Sovacool 2014). According to Hess and Sovacool (2020), in the last decade, these contributions have moved social sciences from being peripherical to energy transition matters to being just as important as the engineering sciences. They have conceptualized energy as being enmeshed with multiple social dimensions such as economic incentives, organizations, technology usages, energy perceptions, markets and policies, cultures, and so forth (Sovacool et al. 2015). 'Sustainable energy system transition' has become a paramount object of inquiry in the social science literature, with its own academic networks (i.e., the *Sustainability Transition Research Network*) and journals (e.g., *Energy Research and Social Sciences*, *Energy and Society*).

Despite being an interdisciplinary field embracing different perspectives, approaches, and methods, the most prominent theoretical framework draws on the field known as 'Transition Studies' (Hess and Sovacool 2020). Transition Studies encompass an array of conceptual approaches developed from the 1990s onwards drawing, most notably, on evolutionary economics (Köhler et al. 2019). Transition Studies include the Strategic Niche Management (SNM), the Multi-Level Perspective (MLP), and the Technological Innovation System (TIS) approaches (Kemp 1994; Geels 2002; Carlsson and Stankiewicz 1991). Overall, these three approaches are concerned with long-term processes of technological change towards sustainable patterns of production and consumption. They are often used to investigate technological innovations through historical and longitudinal studies. These authors assert that successful technological innovations follow an S-curve evolutionary path from invention, to diffusion and, to large-scale implementation (Köhler et al. 2019).

Authors in the field of Transition Studies claim that established technological systems and their actors – the technological regime – benefit from increasing returns and, consequently, represent a barrier to sustainable infrastructure change. Kemp, Schot and Hoogma (1998), key proponents of the theory, define a 'technological regime' as:

> … the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills

> and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures (Kemp, Schot, and Hoogma 1998, 340).

Transition Studies scholars argue that radical technology innovation is hindered by established regimes. Because the engineers, institutions, technologies, and practitioners in the field share a common understanding of problems and solutions, they tend to exclude alternatives and favor incremental solutions. Therefore, these actors will seek, "*regime optimization rathen than regime transformation"* (*ibid*., 182). Accordingly, Transition Studies scholars argue that radical technology innovation can solely come from 'niches', protected spaces where innovations can thrive without facing regime constraints (Kemp 1994; Geels 2002; Carlsson and Stankiewicz 1991).

Niches are the places where things can be tested. The term 'niche' may, for example, refer to a company, a research institution or a geographical space where a new technology can be created, tested by specific users, and ameliorated until an optimal design is found. Niches are protected from social opposition, policies and market dynamics. According to Transition Studies scholars, niches are essential seed-of-change providers for regimes (Kemp 1994; Geels 2002).

Having a structural ontology, the scholars maintain that the actors and elements of the field have intrinsic properties, and, hence, they categorizes them to reduce the messiness of the world (i.e., incumbent/challengers, micro/macro, local/global). Using technology diffusion as the unit of analysis, Transition Studies are commonly based on historical documents; they aggregate facts and events to draw conclusions about the world (Garud and Gehman 2012).

Although the three approaches share the same conceptualization of barriers to change, they highlight slightly different aspects of technology transitions. In what follows, I provide a brief overview of the three approaches and their findings regarding district heating transitions. I also discuss the main critiques and debates with regard to each of the three approaches.

2.3.1. STRATEGIC NICHE MANAGEMENT AND GOVERNING TRANSITIONS

2.3.1.1 The Strategic Niche Management (SNM) approach

SNM scholars argue that managing the 'niches', the protective spaces where innovations can emerge, "*may be the only feasible way to transform environmentally unsustainable regimes"* (Kemp, Schot, and Hoogma 1998, 191). According to them, technology innovations do not emerge from strategic activity, but from peripherical R&D developers, who do not address regime lock-ins. Accordingly, SNM scholars assert that innovations that are not managed and taken into strategic activities have little chance of breakthrough in the regime (*ibid*.).

Consequently, SNM scholars posit that technological innovation processes must go hand-in-hand with managerial activities. Shaping users' perceptions, influencing engineers' beliefs, and modulating market expectations are some of the activities that constitute 'strategic niche management'. These activities are said to permit better *adaptation* and *articulation* of the technology into the established regime (Kemp and Loorbach 2003; Smith, Stirling, and Berkhout 2005).

Moreover, SNM scholars argue that clear visions and consensus-making can generate better transitions (Kemp and Loorbach 2003). Proponents of the theory claim that societies often choose goals implicitly, and that strategic management can allow these goals be to re-oriented towards sustainability. Kemp and Loorbach (2003) argue that, "*transition goals should be translated into transition visions*" (p. 14) and that they can then be, "*translated into the institutional, economic, ecologic and socio-cultural aspects",* hence leading to consensus-making and clear path developments. Even though SNM scholars acknowledge that, *"transitions are impossible to predict, fully comprehend, or steer directly*", there are, nevertheless, "*patterns of change that can be anticipated*" through consensus-making and the development of clear strategic visions (Loorbach, Frantzeskaki, and Lijnis Huffenreuter 2015, 50).

In recent developments in the approach, SNM scholars have shifted the discussion from management to governance issues (Köhler et al. 2019). The discussion started with that not only top-down governance can make a difference in niche management processes and noted that (other) actors and institutions may play a role in shaping policies and governance (Kern and Howlett 2009). Therefore, more recently, authors in the field of SNM have focused on identifying which intermediary actors, policies, and regulations should be adjusted to support niche empowerment and breakthrough in the regime (Smith and Raven 2012; Köhler et al. 2019).

2.3.1.2 SNM and DH transitions

In a recent study, Bush et al. (2017) consider DH in the UK as a niche innovation that has yet to breakthrough in a regime predominantly supplied by gas. Using the SNM approach, the authors look at the role that intermediary actors play in empowering the DH niche, thereby assisting its diffusion into the regime. In order to understand the interactions between the actors involved in district heating development processes, Bush et al. (2017) organized a workshop with local energy officers, energy managers, energy community representatives and local entreprises. The idea was, "*to facilitate collaborative decision making between a group of relevant stakeholders in a complex group decision process*" (p.140). The scholars presented three district heating infrastructure development stages (i.e., pre-feasibility, feasibility and delivery), and aimed to generate a managerial consensus among the participants. From the results of the workshop, the scholars identified that, because of the geographically bounded nature of district heating, local actors (who they define as, "*the local authority, housing associations or the local university*" (p.141), were the most important stakeholders in terms of facilitating infrastructure expansion. However, they found that these actors had limited power compared to national actors; something which they identified as being a predominant challenge to the breakthrough of district heating in the regime. They conclude:

> District heating, by its nature, requires local support and coordination. This meant that the under-resourced local intermediary function within the case study was a key challenge. Re-structuring of the institutional framework is likely to require the re-distribution of resources and power from existing institutions (Bush et al. 2017, 146).

The scholars then conclude that there is a need for shielding policies on district heating technologies, as well as the redistribution of resources and agency from the national to the local level in order to empower the key local actors.

In another study, Bush and Bale (2019) investigate the role of energy planning tools in supporting district heating niche management in the UK. They examine different types of heat mapping tools and their various uses in planning processes. The authors conclude that maps may demonstrate the potential of district heating infrastructure to stakeholders unfamiliar with the technology, and that, consequently, they may have a significant role to play in facilitating technological breakthrough. They conclude:

> [H]eat mapping tools have the potential to form an evidence base for local strategic planning for district heating (Chittum & Østergaard 2014). This type of strategic planning can be used alongside regulatory powers or incentives to drive development of large scale, interconnected networks that offer larger benefits for the wider energy system (Woods et al. 2005). Use of heat mapping for local strategic planning could, therefore, be seen as a form of niche empowering process within the case study (Bush and Bale 2019, 2202).

The scholars conclude that maps can have a significant role to play in decision and consensus making processes, and suggest that further research should investigate how different tools may facilitate different strategic niche management objectives.

To my knowledge, no other SNM studies have examined DH as a niche innovation, although scholars have studied other forms of infrastructure or energy resources such as biofuels (van der Laak, Raven, and Verbong 2007), biomass gasification in India (Verbong et al. 2010), or the solar electricity sector in Lebanon (Thornton 2016).

Despite providing insights into the conditions facilitating the shift of energy resources into regimes, SNM studies have been subject to criticism, which is discussed in the following.

2.3.1.3 Criticism of the approach:

One of the main critiques of SNM is that, "*it pays limited explicit attention to agency and institutions*" (Geels et al. 2016, 896). Built on the underlying assumption that a well-managed niche will lead to the successful diffusion of a technology in society (Köhler et al. 2019), SNM scholars, according to critics (Geels et al. 2016; Geels and Johnson 2018), have neglected the role of agency and the wider institutional environment. Roberts and Geels (2019, 1082) criticize these studies for, "*mostly focusing on the development of sustainable innovations in early phases, rather than addressing wide diffusion and system change*", and claim that they only offer partial insights into system transitions.

Furthermore, SNM scholars have conceptalized niche management as a coherent consensus-making activity in which clear visions of the future are essential (Kemp 1994). They have attempted to identify possible redesigns of policies to strategically accompany technological innovations and the formation of well-defined outlooks (Loorbach, Frantzeskaki, and Lijnis Huffenreuter 2015). Nevertheless, scholars have identified the presence of ambiguities, tensions, and uncertainties in transition processes (Shove and Walker 2007; Jensen et al. 2015; Jørgensen 2012). Jensen en al. (2015) for example argue that transitions are processes of '*navigating uncertainties'* rather than clear path-making and that amending policies amendment is insufficient for achieving the desired outcomes. Arguably, this has led SNM scholars to, "*black box the potential transformative implications of conscious strategic maneuvering by incumbent regime actors"* (Quitzau et al. 2013*,* 141). Furthermore, according to Smith, Stirling and Berkhout (2005), it has also led SNM scholars to, "*treat regime transformation as a monolithic process dominated by rational action and [to] neglect[ing] important differences in context*" (p.1492).

In other words, SNM scholars have been criticized for being too interested in the object of governance (the rules, policies, and strategies) rather than the agency processes of governing (the work and navigations). Their approach has been criticized for simplifying processes of technology innovation and diffusion, imposing who and what could bring about these innovations, and for having a narrow and pre-defined understanding of contexts and uncertainties.

2.3.2. MULTI-LEVEL PERSPECTIVE AND THE ROLE OF INCUMBENT/CHALLENGERS

2.3.2.1 The Multi-Level Perspective approach

The Multi-Level Perspective (MLP) is a conceptual approach proposed by Geels (2002). It suggests that the niche, regime, and the landscape levels should be structured hierarchically to conceptualize the dynamics of socio-technical change. As in SNM, the niche is a protected space from which innovations may emerge, while the regime is a sphere that is composed of established incumbents, norms, and regulations that tend to resist change. The landscape is the final layer of the hierarchical structure, which Geels describes as an exogeneous sphere where shocks can occur (e.g., war, pandemics, economic crisis). Geels (2002) notes that, *"[t]he different levels are not ontological descriptions of reality, but analytical and heuristic concepts to understand the complex dynamics of sociotechnical change*." (p.1259). The theory is considered a general conceptual framework on which other theories may hinge (Geels and Johnson 2018; Geels 2019).

In MLP, established actors within regimes are categorized as incumbents, i.e., they have a position of authority and power (Turnheim and Geels 2019). These actors are considered to be against regime change, as a change could result in their losing their agency. Also, these actors are said to benefit from reverse salients and economies of scale, and to participate in coordinating and stabilizing the social, economic, and institutional dimensions of the regimes. They are, hence, considered to have the agency to hinder innovation breakthroughs, and are categorized by MLP as a source of lock-ins of existing technologies.

However, although the established regime with its set of rules, actors and dynamics has power and supports the status quo, Geels (2004) argues that technological innovation may occur if tensions arise and destabilize the stability of the regime. For example, an event happening at one level (an exogeneous crisis such as a war or oil crisis) can influence and transform the regime, which then can generate pressure and tension between the regime and the niche. This pressure may result in a "window of opportunity" for radical innovations to breakthrough the regime. According to MLP, these windows of opportunity are rare. Geels (2004) explains:

> As long as ST[socio-technical]-regimes are stable and aligned, radical novelties have few chances and remain stuck in particular niches. If tensions and mismatches occur, however, in the activities of social groups and in ST-regimes, this creates 'windows of opportunity' for the breakthrough of radical novelties (Geels 2004, 914).

Accordingly, the MLP approach conceptualizes chance as playing a substantial role in transition processes, as it can enable windows of opportunity to be created. And once such a window is open, the innovative technology embarks on a path which, through self-reinforcing mechanisms, will lock the regime into a new system. In other words, once embarked on its path, the evolution of the technology is quasi-determined. Additionally, because MLP identifies the moment when the innovation starts and when the new regime is established, the theory is said to allow one to conceptualize, "*the time scale of energy transitions",* which "*perhaps obviously, must be measured over time*" (Sovacool 2016, 203).

In more recent contributions to MLP, Geels et al. (2016) has attempted to (re)introduce agency and institutions as core elements of the theoretical framework. According to the authors, only "*limited explicit attention*" (p.896) has been paid to these two elements by Transition Studies scholars. Consequently, they emphasize that MLP can account for the conflicts and struggles between actors by, "*develop[ing] the 'local' logic of the transition pathways*", where 'local' refers to, *"the immediate action processes*" (p.897). Geels et al. (2016) maintain the global/local dualism, and argue that it can enable the articulation of, "*the link between agency and field-level trajectories*" (p.897).

2.3.2.2 MLP and DH transitions

Geels and Johnson (2018) note that district heating has received very limited attention in the MLP and transition studies literature and that it should receive more , "*because district heating is a complex technical system"* that "*fits the low-carbon agenda*" (p.143). In pursuit of this agenda, the scholars study the evolution of Austrian district heating and extend MLP with "Diffusion of Innovation Theory" (DIT). Geels and Johnson's (2018) aim is twofolded: they want to contribute to the DIT literature, which has, "*limitations with regard to system diffusion*" (p.139) (and to which MLP can contribute), and simultaneously show that other theories can hinge on MLP. Based on a longitudinal study, Geels and Johnson (*ibid*.) identify the elements that enabled district heating systems to breakthrough from the niche to the oil-based regime level in Austria. The combination of MLP and DIT allows them to conclude that the "regime-to-niche" interactions decreased over time, whereas the "niche-to-regime" interactions increased. According to the authors, identifying the tipping point where the latter type of interaction becomes predominant permits one to refine the, "*temporal understanding of system diffusion*" (p.138) which, they argue, has been under-conceptualized in transition studies.

Roberts and Geels (2019) also aim to contribute to the limited attention paid to DH by MLP studies by comparing the transitions from oil to natural gas in the Netherlands and from oil to district heating in Denmark in the 1970s. The scholars analyze how policymakers can, "*deliberately accelerate energy transitions*", and "*particularly in light of resistance from incumbent actors*" (p.1082). Based on historical documents, they identify the main key events in the two studied countries and conclude that in each instance, specific policies had 'accelerating' effects on the transitions: the 1962

Natural Gas Agreement in the Netherlands, and the 1979 Heat Supply Act in Denmark.

In the Danish case, Roberts and Geels (*ibid*. p.1099) note the absence of "*incumbent firms*" in the regime and identify the municipalities as the "*new entrants"*. However, this conclusion seems slightly contradictory as the Danish Government itself (categorized as being a central regime institution) tasked the municipalities with being responsible for developing district heating. Therefore, the municipalities can hardly be considered 'new entrants' as suggested by Roberts and Geels (2019), because they are not "powerless actors" trying to destablized the established regime. Furthermore, the authors do not explain the absence of 'incumbent firms' or define what is meant by 'accelerated' socio-technical transitions.

This issue of identifying what constitutes a niche and/or a regime was also highlighted in an earlier study on DH transition (Di Lucia and Ericsson 2014). Using MLP to examine the district heating transition in Sweden from 1960 to 2011 and based on document analysis, Di Lucia and Ericsson (2014) show that phases of "*de- and re-alignment*" (p.18) between regime and landscape elements led to a transition pathway in the Swedish DH infrastructure. The authors analyze the elements that have weakened some core actors and have led to the formation of a new biomass-based district heating regime. They argue, for example, that 'landscape elements' (i.e., the oil crisis) resulted in the collapse of the existing regime and that 'niche elements' (i.e., R&D programs supporting biomass) led to the establishment of a new low-carbon energy regime. Di Lucia and Ericsson (*ibid*.) then conclude that MLP fails to provide contextualization to delineate which element belongs to which level. They argue as follows:

> [T]he MLP (...) presented some challenges, in particular, with regard to the operationalisation and specification of the concept of socio-technical regimes, which can be defined at different empirical levels. For example, within the area of DH, the regime could be studied at the level of primary fuel (coal, oil, gas), or at the level of the entire system (production, distribution and consumption of heat) (...). Consequently, what appears to be a regime shift, i.e. a transition, at one level, may be viewed merely as an incremental change in inputs for a wider regime at another level (Di Lucia and Ericsson 2014, 24).

Di Lucia and Ericsson (2014) then warn that such ambiguity in terms of the delimitation of the different levels provided by MLP may lead to weak analytical discussions. They, therefore, argue for the need to reconsider the unidirectionality or bidirectionality of the interactions in a studied system to define their levels. However, as their suggestion still approaches the world with a distant and structuralist perspective, it may not allow one to get closer to the action or to the 'context' in which it unfolds.

Carrosio and Scotti (2019) also use MLP to investigate developments in district heating. They compare two technologies, namely district heating and wind power, in urban and rural areas of Italy. Having reviewed national statistics, government documents, main power company's websites, and conducted a few interviews with representatives of wind power and district heating systems, the scholars conclude as follows concerning the effect of territorial bounds on regime transitions:

> [T]he transition process appears with different speeds and forms depending on the territorial contexts that influences the modalities of spread of technological energy devices across national local contexts. In our study, the district heating and the wind power produced ambivalent outcomes in the territories in which they were implemented (Carrosio and Scotti 2019, 690).

Carrosio and Scotti (2019) then suggest that regimes should be approached as "*techno-institutional territorial complexes*" and argue for the need to add a territorial dimension to MLP theory to account for the spatial modalities influencing technological transitions. However, adding a territorial dimension without changing the structural lense of analysis may not allow one to get any closer to the situatedness of action and agency or to the role the materiality of the technologies plays in the transitioning processes (Garud and Gehman 2012).

2.3.2.3 Criticism of the MLP approach

As seen above, one of the main criticisms of MLP is the difficulty in establishing clear delimitations as to whom/what defines actors as 'new entrants' or 'incumbents' and, similarly, what defines the landscape, regime, and niche levels (Di Lucia and Ericsson 2014; Köhler et al. 2019). In response to some of this criticism (the scholars do not address the criticism directed at the categorization of levels), Turnheim and Geels (2019) propose a slightly different use of MLP to conceptualize 'incumbency'. In a study of the French tram system, Turnheim and Geels (2019) conclude:

> Our finding with regard to the positive role of incumbent actors suggests that niche-regime interactions should be studied symmetrically. We therefore propose that scholars not only analyse niche-to-regime activities (which currently dominates the literature), but also regime-to-niche activities. The latter may include strategic reorientation of incumbent actors in the focal regime (...) or of incumbent actors in neighbouring regimes (as in our case) who present significant relatedness or proximity advantages. The latter may offer a way to mobilise counter-veiling power against locked-in focal incumbents, not just in a political sense (Hess, 2013), but also in terms of capabilities and financial resources (Turnheim and Geels 2019, 1425).

Therefore, Turnheim and Geels (*ibid*.) address the criticism in saying that it is rather the researchers themselves who have misunderstood MLP concepts. They assert that the theoretical approach is capable of providing a nuanced perspective and clarity to the role of incumbent actors if the interactions between the levels are studied symmetrically. However, despite aiming to bring nuances regarding which actors have agency over a technological pathway, defining the actors' categories with greater precision will not allow one to capture agency and actions as it maintains structural dualisms (global/local, powerful/less, etc.). Consequently, there is a risk that Transition Studies scholars will move even further away from the messiness of the field as a result of their demands for clearer delimitations.

In a similar vein, Sovacool, Axsen, and Sorrell (2018) and Turnheim and Sovacool (2020) assert that there is a need for greater rigor in energy research when using MLP (and Transition Studies) concepts. Turnheim and Sovacool (2020) *"argue that transitions research needs to engage more firmly with the role of incumbents and various forms of incumbencies"* (p.180). They then propose the following four methodological steps to ensure that MLP scholars have a more nuanced approach to incumbents: acknowledging the diversity of incumbent types, the diversity of incumbents' strategies vis-à-vis regimes, their temporal evolutions, and their respective access to resources. If these steps allow MLP scholars to refine their understanding of 'incumbents', there is a risk that they will deviate even further from the messiness of the field, as the pre-categorization of actors 'out there' may make them blind to the agency and the making of action (Garud and Gehman 2012).

Further criticism is related to the conceptualization of time and space and how 'energy transition' is defined under MLP. Regarding time, Grubler, Wilson, and Nemet (2016) have, for example, criticized Sovacool (2016) for measuring the flows rather than stocks of the Brazilian energy transition, as well as for being mistaken regarding the elements that account for the beginning and end of the transition. Grubler, Wilson, and Nemet (2016) argue as follows:

> By adopting an upper threshold of 25% for his definition of rapid changes, Sovacool *ex ante* has shortened the transition times of his examples by a factor of two compared to the evidence reviewed from the historical transition literature he cites which uses an upper threshold value of 50%. The comparison is therefore not made on a like-for-like basis and so is misleading (Grubler, Wilson, and Nemet 2016, 18).

In response to these critics regarding the temporal dimensions of energy transitions (see, for example, Fouquet 2016; Smil 2016; Grubler, Wilson, and Nemet 2016), Sovacool and Geels (2016) countered that they purposefully aimed to provoke and create a debate. Sovacool and Geels (2016) then argued for the need to reframe, "*what fast transitions accomplish, or what slow transitions prevent from occurring*" (p.236), and stressed that MLP can be used to categorize and discuss the pace of energy transitions. However, by holding onto predefined categories, Sovacool and Geels

(2016) are limited in terms of capturing the specific socio-technical networks in their particular (temporal) settings. The MLP approach only allows one to infer change as a result of aggregated events but not to follow the action as it unfolds (Garud and Gehman 2012).

In keeping with Carrosio and Scotti (2019), geography-inspired scholars (see, for example, Hansen and Coenen 2014; Gailing and Moss 2016; Labussière and Nadaï 2018; Carrosio and Scotti 2019) have noted that the spatial dimensions have remained largely ignored by MLP scholars. Despite acknowledging the "*context-specificity of local projects*" (Geels 2019, 193), the MLP literature has been criticized for not addressing the geographies and materiality of transitions, as expressed by Bridge et al. (2013):

> [I]t is the temporal concept of 'transition' – rather than a geographical alternative – that is most often mobilised for thinking about the changes involved in developing low-carbon energy systems. (...) '[T]ransition' readily captures change over time for a given geographical unit (e.g., a country or a region) but frequently overlooks changes in the spatial organisation of the energy system and economic activity more widely (Bridge et al. 2013, 332).

The scholars note that some studies have intended to add a geographical dimension to MLP, but without systematically addressing the influence of scale and space on transition processes. Other authors have also criticized MLP for not adressing the materiality of energy infrastructures and resources (Birch 2016; Labussière and Nadaï 2018). This taken-for-granted aspect is considered by these critics to obscure the importance of the materiality and geographical dimensions of technologies,which co-construct energy transitions. Because it assumes that the materialities and spatial dimensions of technologies do not co-transform the world in which they exist, MLP appears to fall short in terms of capturing the messiness of the ongoing actions.

2.3.3. TECHNICAL INNOVATION SYSTEMS (TIS): THE ROLE OF SPACE AND LOCAL MARKETS

2.3.3.1 The Technological Innovation System approach

Technological Innovation Systems (TIS) is another strand of thought within Transition Studies with a particular emphasis on spatial dimensions. Similar to SNM and MLP, the main focus is on technological innovations, the conditions under which they develop and thrive, as well as those that constrain them. However, the main difference is that TIS has more of an 'economic' or 'sectorial' approach and it breaks away from the layered regime and landscape concepts proposed by SNM and MLP. Authors in the field of TIS focus on the specifics of each technological field, i.e., performance and development potentials, and are less interested in the stability of systems (Carlsson and Stankiewicz 1991; Bergek et al. 2008; Malerba 2002).

Furthermore, TIS scholars assert that two innovation processes cannot be compared because the performance, characteristics, and spaces in which the technologies develop necessarily differ. Bergek et al. (2008) define TIS as follows:

> [S]ocio-technical systems focused on the development, diffusion and use of a particular technology (in terms of knowledge, product or both). TISs do not only contain components exclusively dedicated to the technology in focus, but all components that influence the innovation process for that technology. A TIS may be a sub-system of a sectoral system (...) or may cut across several sectors (...) (Bergek et al. 2008, 408).

TIS approaches have more of a sectorial perspective than SNM and MLP do, and, accordingly, there is greater emphasis on the role of knowledge diffusion, entrepreneurial activities, resource mobilization, and market mechanisms. Another significant feature of TIS is that it addresses the geographical factors of technology innovations, unlike SNM or MLP (T. Hansen and Coenen 2014; Markard, Raven, and Truffer 2012). Consequently, TIS scholars see space not solely as the locus of transition but also as a part of the transition itself. Hansen and Coenen (2014) argue as follows:

> Transitions are constituted spatially and unpacking this configuration will allow us to understand better the underlying processes that give rise to these patterns. This requires analysis of the particular settings (places) in which transitions are embedded and evolve, while at the same time paying attention to the geographical connections and interactions (i.e. the spatial relations) within and between that place and other places (T. Hansen and Coenen 2014, 95).

They argue that spatialities shape energy transitions as they constrain and/or allow certain types of socio-technical developments, and vice versa, sociotechnical developments have different impacts on the landscape (Dewald and Truffer 2012; Bridge et al. 2013; Hansen and Coenen 2014).

2.3.3.2 TIS and DH transitions

Despite being recognized as a prominent contribution to the transition study literature, to my knowledge, TIS has only been applied by Hawkey (2012) to investigate district heating transitions. Hawkey (2012) uses TIS to study how district heating, which is considered a niche technology, could be widely developed in the UK, which is considered a gas regime. He notes that the technical district heating components are relatively mature as they have been deployed in the Nordic countries successfully, but that there is a need to understand the organizational, commercial, and contractual barriers of the '*inherently local infrastructure'*. Hawkey (2012) identifies seven sub-functions of the DH system as proposed by Bergek et al. (2008) including entrepreneurial experimentation, resource mobilization, and knowledge development, among others. These sub-functions are used to account for the specificities of district heating in the UK. After analyzing these, Hawkey (2012) concludes:

> The embeddedness of DH in the UK's other energy systems creates a set of blocking mechanisms. DH faces difficulties finding a place in electricity systems physically and institutionally designed around a centralised model of provision. Over the long timescales implied by DH financial models, uncertainties in both energy prices and the mix of other low carbon technologies deployed challenge confidence in future revenue streams. Its exclusion from many policy-informing models of future energy system scenario further marginalises DH (Hawkey 2012, 29).

Hawkey (2012) thus identifies district heating as a technology which has been marginalized by the established regime, which promotes gas and centralized electricity production, thereby limiting its technological diffusion. However, while Hawkey attends to "*local market formation barriers"* (p.25) to district heating diffusion, he does not clearly address what is meant by "local" or "large" scales, nor does he address the market devices supporting the practitioners (Muniesa et al. 2007).

This is also noted by Dewald and Truffer (2012) (key proponents of the approach), who argue that there is a general, *"lack of an explicit spatial dimension when analysing market formation"* (p.401) in the TIS literature. To address this drawback and contribute to the literature, Dewald and Truffer apply the TIS framework to the emergence of the German PV industry with a focus on market formation. Their analysis demonstrates that, "*locally bound market processes*" have led to various PV successes in Germany and highlights the importance of the "*available local resources"* (p.400). The authors conclude that, "*early local market formation processes"* are important for the success of the German PV industry (p.415). Dewald and Truffer (2012) thus claim that local contexts and existing available resources can overcome local innovation barriers, and they even conclude that early market formation may be the "*very basis"* for innovation success (p.400). The scholars are, however, not explicit in terms of what is meant by local/global, nor do they address the tools that assist the market formation processes. From this perspective, the practitioners in the field are rational economic actors based solely on their cognitive competencies (Muniesa et al. 2007; Callon 2008).

2.3.3.3 Criticism of TIS

In their recent literature review in which they lay down a research agenda for energy transition research, Köhler et al. (2019, 14) assert that the TIS literature is still, "*primarily concerned with understanding how and why transitions are similar or different across locations"* and that it only offers, "*spatially nuanced regimes"* perspectives. In other words, despite trying to break away from the layered SNM and MLP concepts, TIS authors have received the same criticism as transition studies in general.

Other authors have also criticized TIS scholars and transition studies scholars in general for taking space, geographies, resources, and technologies for granted and assuming their pre-existence (Nadaï and Horst 2010; Labussière and Nadaï 2014). Labussière and Nadaï (2014), for example, argue that assuming technologies or renewable energy resources have intrinsic properties is restrictive. They argue as follows:

> [This approach] fails to acknowledge the role of the processes through which renewable energies achieve their territorialization and emerge as a new reality. (...) In other words, because this intellectual framework defines the potential as an intrinsic attribute of the technology, the social dimension is framed as separated from the technology and as a 'barrier' (local opposition, administrative procedure) to the achievement of the 'technological potential' (Labussière and Nadaï 2014, 154).

The understanding that resources and technologies are pre-given rather than continuously emerging entities has been identified as a key limitation of the analytical perspectives within the social sciences (Bulkeley 2019). Furthermore, Köhler et al. (2019) have also identified the need to go beyond the idea of technology transfer (i.e., that a successful technology in country A can also be successful in country B), and have argued for the need to explore the results of urban and local technological experimentations without a comparative angle.

Moreover, despite aiming to address market formation mechanisms and entrepreneurial activities, TIS does not investigate them closely. TIS scholars talk about them and, in aggregating facts and events, make claims and draw conclusions, but they still do so with an outsider's view. TIS emphasizes concepts (such as market formation, market phases, etc.), which simultaneously hides the actions of market formations and mechanisms. Furthermore, despite mentioning entrepreneurial activities, TES scholars do not address the means, the devices, through which these activities unfold (such as business models, negotiations, strategies, etc.) (Muniesa et al. 2007).

Moreover, scholars of social practice theory have demonstrated that technology producers and managers, "*are unable to control the fate and fortune of the things they make*" (Shove and Walker 2007, 768) because consumers, considered as external to TIS, play a significant role in technology adoption. They have argued that influencing the innovation process may not lead to the expected outcomes, and that the diversity of actors should be recognized. Consequently, Shove and Walker (2007) conclude that more caution is needed in regard to the deterministic approach of TIS and Transition Studies in general.

2.4. REVISITING DISTRICT HEATING TRANSITIONS?

This chapter has reviewed the main contributions to the district heating transitions literature. Engineering, economics and transitions studies are the three key disciplines that have offered insights into the phenomenon. The engineering contributions have identified a sustainable technological district heating future, the economists' contributions have emphasized the role of business models for power utilities to adapt to the new types of energy resources, and finally, Transitions Studies have identified the path-dependent processes through which energy transitions may occur.

Each of these three main disciplines has its own problem-solution pairing of district heating transitions. For engineers, the problems can be solved technically but are hindered by institutions and, therefore, they promote regulation change (e.g., tariff structures or policies). For economists, district heating transition is a matter of establishing the 'right' business model (one that permits utilities to reveal the intrinsic properties of new technologies) and, therefore, they promote specific business model components. For transition studies scholars, transition is a matter of tensions between niches and regimes and they, therefore, promote overcoming barriers to regimes through better management, strategic visions and coalitions, among others. However, transition studies represent a strand of thought that encompasses different conceptual approaches, i.e., SNM, MLP, and TIS, each of which has slightly different perspective on how to address regime barriers.

The following section revisits some of the main critiques that have been directed at the Transition Studies literature, which I supplement with my own. This is followed by a section which introduces the relational approach I use in this inquiry, thereby paving the way for the theoretical contributions developed in chapter 3.

2.4.1. PRE-DETERMINED FRAMEWORKS BLIND TO ACTION

According to SNM scholars, energy transitions can be achieved through better niche management. They have proposed 'empowering' niche technologies as they supposedly have the agency to break through into 'regimes'. For this purpose, they have argued for the need for a clear vision and specific policies and strategy orchestrations (Kemp, Rip, and Schot 2001; Kemp and Loorbach 2003). These proposals have been criticized by other scholars, who assert that transitions are rather the result of navigation activities performed by actors in situations of uncertainty. Consequently, these scholars have argued that clear visions and management alone cannot lead to successful transitions (Quitzau et al. 2013; Smith, Stirling, and Berkhout 2005; Shove and Walker 2007).

MLP informed scholars have defended the hierarchical view of niches, regimes, and landscapes, where tensions between levels can create 'windows of opportunity' for change (Geels 2004). According to them, energy transitions can, therefore, be initiated through pressure from the niche or the landscape on the established regime. However, this approach has been criticized for being unclear as to the delineation of these three different levels, as well as the simplistic conceptualization of 'incumbents' as actors refractory to change (Di Lucia and Ericsson 2014; Köhler et al. 2019). Despite the fact that proponents of the theory have argued that these drawbacks stem from a "lack of rigor" among academics rather than the theoretical approach itself (Turnheim and Geels 2019; Sovacool, Axsen, and Sorrell 2018), they have not proposed a clearer categorization of these levels and actors, nor have they proposed moving beyond ordered accounts of the world. Furthermore, the MLP approach has been criticized for overlooking space and time factors (Hansen and Coenen 2014; Smil 2016).

Moreover, according to the TIS approach, energy transition is a matter of sectoral innovations. TIS scholars have, thus, concluded that transitions can be achieved through knowledge diffusion and entrepreneurial activities (Carlsson and Stankiewicz 1991; Bergek et al. 2008). According to them, these activities are geographically bounded. Other scholars have, however, criticized TIS scholars for black-boxing technologies, resources, and scale (Labussière and Nadaï 2014; Bulkeley, Castán Broto, and Maassen 2014), for not going beyond a territorial perspective on the 'regime' (Köhler et al. 2019), and for only addressing entreprenurial activities from the outside without attending to practitioners' tools (Garud and Gehman 2012; Muniesa et al. 2007).

In addition to these critics, I also note that all three approaches overlook the actions of those involved in the field. Transition Studies scholars use technological (path-dependent) shifts as their unit of analysis, which, consequently, leads them to conceptualize energy system transitions as objects from the past, as linear changes of technology or fuel with a time-lapse in between (Sovacool 2016). Accordingly, they conceptualize 'transitions' as objects that are neatly prepared in niches and then linearly unfold in what they consider to be stable environments. Further, despite searching for more agency (Geels et al. 2016), Transition Studies scholars have an outsider ontology that does not enable them to capture the action. Relying on facts and the aggregation of events, these authors are blind to the work of the actors, their actions, and the ongoing struggles and uncertainties that are present in the field (Shove and Walker 2007; Quitzau et al. 2013; Jensen et al. 2015). Consequently, and despite their ubiquity, the processes of transitioning remain strangely absent from the Transition Studies literature.

Furthermore, Transition Studies scholars have a structuralist ontology, which leads them to approach the field with pre-defined categories to address the messiness of the world. They assume that the elements (the actors, organization, technologies and energy resources) have intrinsic properties. They consider both the elements and the field itself as being fixed entities, and assume that the elements do not co-transform the world in which they exist. This rigid approach to the field renders their empirical analyses distant from the entangled elements and co-evolution processes.

Consequently, authors in the field of energy transition studies have had little to say about the precariousness and co-evolutions of transition processes (Garud and Gehman 2012). Moreover, the materiality of the world (the technologies, spatial characteristics, resources, etc.) are not addressed. Despite the fact that TIS accounts for some technological specificities, and that Geels (2004) qualifies the "*hardness"* (p.911) of technological systems, the literature remains blind to the co-production of the material world, and assume that material properties are inherent and fixed (Birch 2016; Kirkegaard et al. 2020).

Lastly, although Business Model Innovation scholars have identified the important role business models play in terms of power utilities achieving transitions (Richter 2012; Helms 2016), while Bush et al. (2017) have noted the importance of planning tools, the apparatus that equips the practitioners in their work of transitioning has been mainly ignored in the transition studies literature. Transition studies scholars talk about the actors in the field as if they were 'naked', as if they only had their cognitive competencies and were unequipped. However, the role that tools and devices play in equipping the actors in their work has been highlighted by other scholars as being of paramount importance in terms of the capacity for action granted to the actors (Miller and Rose 1990; Callon 1998; Muniesa et al. 2007).

The following section discusses what a relational approach to energy system transition would allow in light of the identified drawbacks of the transition studies literature, thereby paving the way for the theoretical contributions informing this dissertation.

2.4.2. RELATIONAL APPROACH TO ENERGY SYSTEM TRANSITION

I intend to develop a theoretical and methodological approach that enables one to examine energy system transitions as they unfold. I want to follow how practitioners reassemble their world in their situation of uncertainty, and to be sensitive to the tools that equip them in knowing, and thus, in acting, in their particular (or 'situated') instances (Callon 1998). Consequently, I propose to approach transitions with a flat ontology, with no foreground or background, and without "levels" of interaction. I intend to change the analytical battlefield from 'far, distant and mechanical' to 'close, messy and ongoing', as also advocated by other researchers (Labussière and Nadaï 2014; Iuel-Stissing et al., n.d.; Pallesen and Jenle 2018). This, I assume, will allow me to follow how transitions are achieved amid their unfoldings. From structured accounts to following the agency, such an insider perspective may enable me to follow the actors' ordering of the world, instead of imposing an ordered world on them. Accordingly, energy transitions may be approached as processes, i.e., precarious ongoing achievements that do not pre-exist themselves.

Such a 'near' approach to transitions may also enable me to transform the taken-for-granted pairing of problem-solution adopted by transition scholars. Currently, transition studies approaches tend to identify the *locus* of the problems before collecting empirical material. For instance, MLP scholars assert that ‘incumbents’ and ‘regimes rules’ are barriers to change. Delving into the messiness of the field with a relational approach avoids pre-defined (and mechanical) definitions of the problem-solution. I want to hypothesize that the issues of transitioning may be more discrete and mundane than inferred by the traditional economics and energy and social science research. Furthermore, this would enable me to approach energy transitions not as the result of ‘collective orchestrations’ but rather as emergent and uncertain processes (Jensen et al. 2015).

It would also allow me to embrace the diversity of agents, conflicts and interactions existing in the field, and to follow the action as it unfolds (Shove and Walker 2007; Labussière and Nadaï 2018). The flat ontology, which addresses heterogeneous actors (i.e., human and non-human) symmetrically, is said to allow one to address resources, technologies, sites, and transitions as co-constructions. Instead of taking heterogeneous actors’ properties for granted, the flat ontology (in contrast to the structuralist ontology of transition studies scholars) allows one to conceptualize actors as outcomes of particular instances (Callon 1986a). In other words, I want to conduct an inquiry into energy system transitions which considers them as being inherently situated and material, but without imposing any intrinsic properties on the technologies or sites inquired.

This ‘nearness’ may also allow me to address the tools and devices equipping the actors in their work of reassembling their worlds. Instead of approaching actors as ‘naked’ rational economic actors, who rely solely on their cognitive competencies, the attention to the devices and information available to the actors may provide new insights into the means that either assist or hinder practitioners in realizing transitions.

In conclusion, it appears that there is room for contributions to the social science literature on energy system (and DH) transitions. By suspending the outsider structural approach advocated by Transition Studies scholars, and shifting to an insider and flat ontology, agency and action can be placed at the center of the analysis, which may result in a more nuanced understanding of the processes behind energy system transitions. The identification of these contributions paves the way for the theoretical considerations informing this thesis, which are developed in chapter 3.

CHAPTER 3. THEORETICAL FRAMEWORK

As seen in the previous chapter, social science studies of district heating transitions have provided numerous insights as to how change may occur in large-scale technological systems. Nevertheless, these approaches have tended to apply pre-made frameworks of analysis and, thereby reducing the messiness of the world into ordered accounts. Furthermore, the studies have put technological innovations at the forefront of the analysis, and have overlooked the relational character of actors, technologies, materials, devices, time, and space as elements co-constructing energy transitions.

Therefore, in order to contribute to the existing social science and district heating literature, I propose approaching energy system transitions with a relational approach. Drawing from Science and Technology Studies (STS), this chapter first develops the Sociology of Translation, a constructivist approach that has received international recognition for reintegrating the role of non-humans (technologies, devices, objects) at the center of the action (Callon 2009). I then develop some insights from The Sociology of Markets which, drawing from the Sociology of Translation, has delved into the role of material devices in enabling actions. These two approaches pave the way for my conceptualization of energy system transition as a precarious and ongoing phenomenon that, I argue, casts energy system transitions in a new light.

3.1. THE SOCIOLOGY OF TRANSLATION

The Sociology of Translation is a constructivist ‘conceptual toolbox’ (Blok, Farías, and Roberts 2020) that conceptualizes the world with a relational and flat approach. Rooted in Science and Technology Studies, the Sociology of Translation criticizes “conventional sociology” by adopting an alternative ontological viewpoint: instead of trying to establish theoretical explanations for phenomena, it emphasizes the messiness of the world and rejects pre-made analytical frames. As the posit of this thesis is to approach energy system transitions as precarious processes in the making and to reject ex-ante explanations, the Sociology of Translation may reveal new insights into the phenomenon.

This ‘conceptual toolbox’ has been gradually enriched and has given way to slightly different concepts which, although based on the same premise, allow one to pose and answer slightly different questions. These concepts are Actor-Network Theory (ANT), the Techno-Economic Network (TEN), and the Socio-Technical network (STA), all of which are succinctly discussed in the following sections.

3.1.1. ACTOR-NETWORK THEORY

Actor-Network Theory (ANT) is a social science approach developed in the early 1980s in the Écoles des Mines (Paris) by scholars such as Callon, Latour, Akrich, and Hennion (Latour 1987; Callon 1986a; Muniesa 2015). The theory adopts a radically different ontological viewpoint than conventional sociology; it approaches the world with a generalized symmetry. ANT has pushed the boundaries of academic disciplines by focusing on the associations between social, material, technical and organizational elements, thereby approaching the world with a flat ontology (Callon 1986a; Muniesa 2015).

Generalized symmetry (or 'flat ontology') is one of the grounding elements of the ANT: it presupposes no difference between human and non-human actors. It claims that there is not, on the one hand, a human world made of intentions, and on the other, a causal material world mobilized by humans (Latour 2005). Rather, ANT postulates that it is from the relation between human and non-human actors (i.e., the actants), that action emerges. Thus, instead of taking as a point of departure an active human related to an inactive material, the starting point is that all the elements composing the networks are active and all have agency, i.e., have the *capacity to act.* For instance, Latour (1988), inquiring about the sociology of a door-closer, shows that action emerges as a result of the association between the individuals and the door-closer; he shows that both the door-closer and the individual have agency, and that the action emerges as a result of their particular association in time and space.

Furthermore, the postulate that action emerges from the relationship between human and non-human actors entails that the action is distributed amongst them, even in cases where it appears as if only one actant is carrying the action. For example, when a plane successfully takes off, it is often imputed to the pilot, but what permits the plane to take off is the relationship between the aircraft, the control tower, the landing runway, the pilot's physical and cognitive competencies, etc. In reality, the action is distributed among the actant parts of the network. Agency is, hence, not pre-given and inherent to actants; it is a network effect (Callon 1986b).

According to Callon (1986a), what leads an observer to conclude that a pilot is conducting the action alone is the effect of a successful *translation*. Translation, he argues, is the process of building associations between actants which, if successful, makes it appear as if only one actant has acted. He explains:

> [T]o translate is also to express in one's own language what others say and want, why they act in the way they do and how they associate with each other: it is to establish oneself as a spokesman. At the end of the process, if it is successful, only voices speaking in unison will be heard (Callon 1986a, 214).

A successful translation makes the pilot, the tower control, the instruments, etc., act as one, imputing the action upon the pilot. However, when a plane crash (unfortunately) occurs, it becomes evident that one of the actants has not been translated successfully. An instrument, an error from the tower control, a bird strike, are all possible sources of the crash, which then reveals the distributiveness of the action.

Therefore, the argument is that a translation always remains fragile, for it is always subject to being undone. In other words, when a chain of actors gives the appearance of stability, each of the actors yet remains to be a possible source of disruption. Maintaining a successful association thus requires a constant work of maintenance, and it is unforeseeable which momentarily silenced actor will suddenly become visible and disturb the established associations (Callon 1986a).

Besides, understanding action as being distributed allows one to follow the elements/associations that provide power and agency to some actants and deprive others. According to ANT, there are no “macro” (organizations, states, institutions) or “micro” (individuals, families, or groups) actors; there are only actors with more or fewer associations. Callon (2006) argues that micro and macro actors are, at the origin, the same, i.e., individuals, but that the difference between the two stems from their past successful associations. It does not mean that actors are isomorphic in their agency, but that their agency must not be taken for granted and should rather be understood as being the result of an achievement. Agency, the capacity to act, is henceforth not inherent to actors, but the result of trials of strength and it always remains precarious as associations (or translations) can always be undone. Concretely, in this view, a power utility is not *de facto* a powerful incumbent that has more agency than a new energy community (Sovacool, Axsen, and Sorrell 2018). Rather, it is an entity which, through successful negotiations and the solidity of its associations to other actants (regulations, customers, energy resources, technologies, knowledge) has more agency than an emerging energy community and, consequently, appears to be a macro-actor. According to Callon (2006, 2009), considering that a power utility is automatically a powerful incumbent (Kemp, Schot, and Hoogma 1998; Geels 2002; Sovacool and Hess 2017) is an anticipation of the solidity of its relations.

In short, ANT allows one to follow the making and unmaking of associations between human and non-human actants, and, consequently, unpack the associations that give agency to some actors while depriving others. Dualisms such as human/non-human, culture/nature, macro/micro make no sense as both humans and non-humans have agency, science and society are co-evolving and shaping one another, micro is linked to the macro and the macro materializes in the micro-processes. Actants are heterogeneous, and so are the relationships between them. This approach can, therefore, contribute to the understanding that district heating transitions in the making do not pre-exist themselves, but are the result of translation and achievement, which always remain precarious.

3.1.2. TECHNO-ECONOMIC NETWORKS

Techno-Economic Networks (TENs) is a concept proposed by Callon (1991), which attends to the dynamics of technological stability and change. Callon (1991, 133) describes TENs as "*a coordinated set of heterogeneous actors which interact more or less successfully to develop, produce, distribute and diffuse methods for generating goods and services*". Consequently, a district heating system can be defined as a TEN. The concept proposes an alternative to economic and sociological explanations of technology evolutions. Callon (1991) explains it as follows:

> TENs are not like networks as normally defined. They bear only a distant resemblance to the technical networks (such as telecommunication systems, railways or sewers) studied by economists. These can, in essence, be reduced to long associations of non-humans that, here and there, join a few humans together. Nor are they reducible to the networks of actors described by sociologists, which privilege interactions between humans in the absence of any material support. Techno-economic networks are composite. They mix humans and non-humans, inscriptions of all sorts, and money in all its forms (Callon 1991, 153).

With TENs, Callon (1991) proposes to move away from the economists' readings, which conceptualize change as being the result of business models successfully revealing intrinsic technological properties (Chesbrough 2010; Helms 2016), and from sociologists' approaches, which conceptualize change as being the result of improved management practices (Kemp, Schot, and Hoogma 1998; Geels 2002). Instead, TEN proposes that technological networks should be approached with a flat ontology, that is, an approach where both the technologies and the social have agency. The concept enables one to avoid the human/non-human duality and to instead talk about "*the-social-and-the-technical*" (Law 1990, 8).

Therefore, the TEN concept offers a new way of conceptualizing district heating transitions. It postulates that technologies and technological systems find longevity as a result of accumulative associations. Callon (1991, 151) argues that "*the past engages the future*" in the sense that the greater the number of past associations established between actants, the greater their degree of convergence and the more likely TENs are to be longstanding and exclude alternative associations. As a result, accumulative associations produce an apparent situation of irreversibility. However, Callon (1991) underlines the fact that the robustness and number of associations between actants says nothing about the future state of the network; the elements composing a network are autonomous and contingent to their own path and can, as such, always diverge from the technological network in which they exist. In other words, a power utility with a solid agency one day can, on another day, lose its agency as a result of the unbundling of past associations.

This also implies that TENs are particular to their past associations and their specific heterogeneous relations. According to Callon (1991), the elements composing a TEN define one another in continuous iterations, they never stop articulating their roles and associations to one another. Accordingly, TENs are necessarily dissimilar to one another because they are the result of particular historical developments, circumstances, and associations. TENs are "*situated*" in the sense that a TEN, in one geographic and temporal site, differs from another. For example, a district heating network in one site is not comparable to another because they inevitably have a different historical development and are made from different elements and associations. Even if the model of technological evolution in each instance may appear to be the same, the elements composing the TEN (in time, space and heterogeneous actors) necessarily differ.

Also, Callon (1991, 140) identifies "*the crucial role played by intermediaries*" in TENs. He argues that intermediaries, that is, the literary inscriptions, technological artifacts, human beings, and money circulating in TENs are the mediums without which nothing can act. He argues that, by circulating, the intermediaries describe and co-shape the networks to which they belong and are, consequently, the mediums that enable actions to unfold. For example, he explains that texts make connections to other texts, extend references and citations, identify and link new facts together, define a reader and a writer and, consequently, co-shape the network to which they belong. Hence, Callon (1991) argues that it becomes possible to analyze the dynamics of socio-technological change by following the circulating intermediaries in TENs.

Therefore, the literature on TENs is in contrast to the literature on transitions as it allows one to break away from the pre-defined categories and analytical frameworks identified in the previous **Error! Reference source not found.**. It offers an alternative t o contemporary technological evolution approaches as it instead approaches district heating actors, technologies, and resources as precarious situated network effects always in the making.

3.1.3. SOCIO-TECHNICAL AGENCEMENT

Continuing to elaborate on the Sociology of Translation and inspired by French philosophers[1], Callon (2007) then proposed the notion of Socio-Technical Agencement (STA), which he describes in the following:

> The term agencement is a French word that has no exact English counterpart. (...) It conveys the idea of a combination of heterogeneous elements that have been carefully adjusted to one another. (...) Agencement has the same root as agency: agencements are arrangements endowed with the capacity of acting in different ways depending on their

[1] See Deleuze and Guattari (1998).

> configuration. This means that there is nothing left outside agencements: there is no need for further explanation, because the construction of its meaning is part of an agencement. A socio-technical agencement includes the statement[s] pointing to it, and it is because the former includes the latter that the agencement acts in line with the statement, just as the operating instructions are part of the device and participate in making it work. Contexts cannot be reduced, as in semiotics, to a pure world of words and interlocutors: they are better conceived as textual and material assemblages (Callon 2007, 324).

STA decorticates the unfolding of action and agency. According to Callon (2008), the analysis of action always poses the analytical problem of affirming that an action did in fact occur – it implies identifying its origins and effects. Sometimes, he argues, this problem is rather easy to solve; it is, for example, quite straightforward to link noise pollution (the effect) to the party next door (the origin). However, sometimes, establishing the link is more complex; for example, a very long chain of observable effects needs to be assembled to link the fossil fuel industry to climate change. The notion of 'agency', and more specifically, 'socio-technical agencement' is, according to Callon (2008), a way to address the richness of actions, their origins, and effects. He explains:

> First, [agency] leaves the uncertainties concerning sources of action open. Who is acting? Is it an individual? A collective? (...) in what forms? There is no general answer to these questions; only the particular circumstances of the action count. (...) Second, the content, nature, and effects of the actions that the agency triggers off are also widely diverse. What differences are produced? How can they be characterized? (...) Third, by restoring the richness and diversity of action and leaving its characterization open, the notion of agency modifies the respective contributions that social scientists and participants in action make towards the analysis of action (Callon 2008, 34).

STA remains open to the diversity of triggers that can provoke actions, as well as the contingencies of their effects. Therefore, by leaving the characterization of action open, STA offers an alternative to transition studies approaches, which impose pre-defined problems, their origins, and effects, onto the field.

STA also allows the situatedness of the actions to be restored: an action unfolds only under particular circumstances in specific STAs, and, therefore, it can not be compared to another. Concretely, the successful action (or translation) of a district heating utility in transitioning towards a so-called 4GDH is specific to the particular circumstances under which the action unfolds, to its 'situatedness'. Accordingly, an action can not be abstracted to a reproducible set of factors in another situated district heating socio-technical agencement. Here, situatedness is to be understood as a set of particular circumstances that are specific to the actors' position in a specific 'agencement', which is not reproducible in another – STAs are necessarily particular to a time, place, and configuration.

Furthermore, Callon (2008, 44) argues that devices "*equip individuals in such a way as to give them a capacity to act*". The postulate is that devices, *irrespective of what they are*" (*ibid*.), extend individuals'/collectivities' capacity for action. A device, he argues, is a tool that compensates for an individual's or a collectivity's inability to act. It restores one's lack of competence, such as energy modeling software for a district heating planner in a situation of uncertainty, or a heat tariff for a heat customer.

Accordingly, STA allows one to conceptualize the capacity to act as not being an inherent property of a human or a non-human, but rather as being the result of a situated 'agencement' configuration. Concretely, district heating technologies or practitioners do not have a pre-given capacity to act: their capacity for action is instead a function of the devices that equip them in the 'socio-technical agencement' to which they belong. Concretely, the capacity for two heat producers to act may differ as a result of their different equipment. For example, one heat producer may be equipped with the energy modelling software 'Balmorel', whereas another one might have internally developed its own software. As a result of their different equipment in analyzing the electricity and CHP sectors, the two producers may have access to different information and, consequently, take different decisions. According to Callon (2008), being sensitive to the devices equipping actors thus allows one to follow the making and unmaking of agency. He concludes:

> [T]he notion of *socio-technical agencement* (...) opens onto a more flexible and richer interpretation of individual agency, as well as a more precise analysis of the conditions under which different types of individual agency can appear and prosper (Callon 2008, 51).

Consequently, the notion of STA can contribute to social science research on district heating transitions by offering a richer interpretation of agency. By being more sensitive to the effects and origins of situated actions and the devices equipping the actors, STA allows one to investigate who/what, in a particular energy system, has the agency to create/hinder change.

Altogether, ANT, TENs, and STA are enhancements of the Sociology of Translation, which all allow one to pose and answer slightly different questions. While ANT is more sensitive to the making and unmaking of associations, the concept of TENs facilitates an understanding of technological development and its dynamics of stability/change. STA, for its part, rather highlights the distributiveness of agency among situated networks, and both TENs and STA emphasize the role of 'intermediaries', or 'devices', for understanding action.

For the purpose of this thesis, the notion of 'Socio-Technical Networks' henceforth encompasses the aforementioned contributions from the Sociology of Translation.

The notion, besides increasing the readability of this thesis, means that the materiality and the associations of technological networks can be brought to the forefront. It enables an inquiry into the situated (un)making of translations, the dynamics of technological developments, and the distributiveness of agency among specific networks. It allows one to approach district heating transitions as phenomena *in the making*, and to do so without pre-defined categories that dictate what may bring about change and to whom.

Besides, the socio-technical network concept highlights the importance of the ‘intermediaries’, or ‘devices’, equipping the actors in transitions. To delve into this relationship even further, the following section develops the core elements of the Sociology of Markets – a line of inquiry which is deeply rooted in the Sociology of Translation and which has specifically attended to this relationship.

3.2. THE SOCIOLOGY OF MARKETS

Stemming from the Sociology of Translation, authors in the field of the Sociology of Markets have delved into the relationship between the tools that equip economists (formulas, business models, and computing tools) and the construction of markets (Callon 1998; Muniesa et al. 2007; MacKenzie, Muniesa, and Siu 2007). They have identified that these tools “*articulate actions. They act or make others act*” (Muniesa et al. 2007, 2), and, as this thesis intends to study energy system transition *in the making*, action lies at the heart of the analysis. Therefore, zooming in on this relationship may refine the analysis of actions in district heating transitions.

The first following section exposes one of the mainstays of the Sociology of Markets, namely, that calculating is a collective practice distributed among cognitive competencies and material devices. The subsequent section develops upon the heterogeneity of devices, in terms of their form and effects, and upon how they allow the distribution of action as a result of their associations with the socio-technical network to which they belong. It also shows that devices can be selective in terms of the manner in which calculations about the world they permit. From this, Callon (1998) developed the notion of *framing*, i.e., the process of making the world knowable and actionable, which results from both a quantitative and qualitative assessment of the world. This notion is thus developed in the third section. Finally, the fourth, and final, section develops upon two approaches proposed by Callon (2008) to ‘re-equip’ actors caught in a situation where they are incapable of acting, namely, through habilitation and prosthesis. These contributions, I argue, enable one to approach district heating system transitions in new ways, without pre-defining who or what has the capacity to act, and inquiring about energy transitions as the result of framing achievements, which always remain precarious.

3.2.1. CALCULATING: A COLLECTIVE PROCESS

One of the mainstays of the Sociology of Markets is that for an actor (which can refer to both an individual or a group of individuals) to take decisions, s/he/it first needs to assess, to calculate, the world in which the decision is to be taken (Callon 1998). An actor must investigate the situation, assess the possible alternatives, explore the different options and consequences, before s/he/it can make a decision. Calculations thus lie at the heart of actions; without calculations, an actor is not able to draw the decisions leading to the action. With a lack of stabilized information or predictions about the future, an agent can still calculate because s/he/it is entangled in a network. Calculating, thus, is more than a mere cognitive process; it is a collective practice. (Callon 1998, 4) explains:

> Calculating (...) is a complex collective practice which involves far more than the capacities granted to agents by epistemologists and certain economists. The material reality of calculation, involving figures, writing mediums and inscriptions (...) are decisive in performing calculations. (...) [W]e should not infer that there are calculative beings, no matter how well or poorly informed they may be. From collective performance we cannot induce individual mental competence.

(Callon 1998) here argues that calculating is a collective action because it is distributed among the heterogeneous actants partaking in the action. He also notes that the equipment to which an actor has access is decisive for its capacity in calculating and, thus, in acting. Concretely, this entails that the same individual, with a different set of devices, has a different capacity for calculation and, thus, of action. Accordingly, as signaled in the quote, the "*figures, writing mediums and inscriptions*" involved in a calculation play a paramount role in terms of who/what can take which action.

3.2.2. DEVICES AND CALCULATING

Devices are central elements in calculation processes and, as flagged above, they can take a diversity of shapes. The following sub-sections develop upon the heterogeneity of devices identified by Sociology of Markets scholars, and then upon their distributiveness and selectiveness.

3.2.2.1 Heterogeneity of devices

In the Sociology of Markets literature, the devices involved in the construction of markets are sometimes referred to as 'calculative devices' (Callon and Muniesa 2005), 'market devices' (Muniesa et al. 2007), 'technical devices' (Hardie and Mackenzie 2007), or 'valuation devices' (Doganova 2020). Muniesa (et al. 2007, 3), for example, defines 'market devices' as "*a simple way of referring to the material and discursive* *assemblages that intervene in the construction of markets*". He argues that analytical techniques, trading software, merchandising tools and trading protocols are 'market devices' because they intervene in the construction of markets. Similarly, Doganova (2020, 259) argues that "*models and plans, demonstrations and formulae, can be analysed as "valuation devices*" because they are involved in valuation processes.

Grandclément (2008), too, follows market devices, but those she follows have a different shape than those identified above by Muniesa (et al. 2007). She argues that shopping carts, price tags, shelves, and sign panels are all material devices that participate in equipping the customers to buy goods without sellers, and are, as such, (super)market devices. For example, she demonstrates how the shopping cart reduces the goods' inconvenience while permitting their stacking which, as a result, configures the customer to buy greater quantities of goods in self-service[2]. As such, she argues, the shopping cart is a physical device involved in (super)marketization. It transforms the actions of the buyer by reconfiguring her/his metrology; in this case, it minimizes the importance of the goods' inconvenience, thereby extending the customer's capacity to buy.

Doganova and Eyquem-Renault (2009) follow another device involved in markets: the business model. They define it in the following terms:

> [T]he business model is a narrative and calculative device that allows entrepreneurs to explore a market and plays a performative role by contributing to the construction of the techno-economic network of an innovation (Doganova and Eyquem-Renault 2009, 1559).

According to the authors, the business model is both a narrative device because it describes a specific venture depending on which audience it is presented to, and a calculative device because it provides numerical elements such as the product price, the expected profits, and costs, etc. Doganova and Eyquem-Renault (2009) demonstrate that what matters is not the veracity and accuracy of the business model, but rather that it permits the construction of the world in which the venture is to exist. They, therefore, conclude that the business model has both a narrative and a calculative dimension, which, together, permits the device to explore different sites and to tie associations bringing a world on its own. Accordingly, they conclude that it is a "*device for exploration*" (Doganova and Eyquem-Renault 2009, 1568). The point of the scholars here is not to categorize the business model as being narrative, calculative or explorative, but to rather show the different elements and effects of the business model as a result of the ways in which business models are being mobilized, i.e., in situated instances.

[2] See also Grandclément and Cochoy (2006) for the shopping cart history (in French).

Therefore, Sociology of Markets' scholars argue that the devices mobilized in calculation processes are not "market devices", "valuation devices" or "exploration devices" *per se* – but that they are so because they are mobilized in a socio-technical network enabling *marketization*, *valuation*, or *exploration*. In other words, Sociology of Markets scholars have shown that devices involved in calculations (and thus in actions) are heterogeneous in terms of their shape and effects. They can be as diverse as software, shopping carts, business models, and inscriptions, and can have calculative, physical, or narrative dimensions. What matters is not the categorizations of the devices as such, but rather being sensitive to their diversity of forms and effects.

This has important methodological ramifications for this thesis: it suggests that one should remain open to the diversity of the devices involved in the actions, as well as remaining open to the contingencies of their effects. This might contribute to a refined understanding of district heating transitions by unpacking how actions unfold in specific sites. In order to encompass the heterogeneity of devices and to bring their materiality to the forefront, this thesis refers to them, henceforth, as 'material devices'.

3.2.2.2 Material Devices: associated and selective

Material devices are heterogeneous and permit action, but they do not do so alone or all in the same way. For example, Grandclément (2008) demonstrates that the shopping cart does not reconfigure the customers' metrologies unassisted; rather, it is the combination of the labels, price tags, brands, product layout, etc., which altogether enable the customers to decide what they want to buy. Consequently, action is distributed not only between the individual and one material device, but among the iterative alignment of the cognitive experiences of the agent ("I have liked this product more than this other one") and the multiple devices distributing the action (signaling 'cheap', 'expensive', 'organic'). As such, the calculative agency of the customers in a supermarket is distributed along with both cognitive competencies and multiple material devices. In a similar vein, MacKenzie (2009) shows that in carbon markets, '*gases are made the same'* as a result of the combination of measurement devices, natural science narratives, IPCC regulatory texts, classification mechanisms, etc. In his study, what permits CO_2 gases to be made into a commensurable product is the combination of material devices. In other words, Sociology of Markets' scholars signal that the success of a material device in enabling action may be contingent on its intertwinement with other devices.

This entails that, when investigating unfolding actions such as district heating transitions, one must be sensitive not only to the diversity of devices being mobilized by the actors, but also to the association of devices with other devices.

Besides, scholars have demonstrated that material devices are selective in terms of what they permit to make actionable. For example, according to Grandclément (2008), the price tags enable customers to rank the cost of goods in supermarkets but they do not allow them to find out how much carbon emissions the goods have generated. Similarly, the electricity bill makes the kWh of electricity used visible to the customer, but it says nothing about the environmental damage caused by the power plants generating the electricity (Stissing et al., n.d.). In other words, material devices make the world visible and actionable in particular ways (Callon 1998).

This entails being sensitive not only to the diversity of devices mobilized in district heating transitions and their associations to one another, but also to what they make visible and actionable, and the different *framings* to which they may lead.

3.2.3. FRAMINGS AND QUALCULATING

As seen above, making the world knowable is one of the fundamental exercises permitting calculation/action. Callon (1998) refers to this process as *framing,* which he explains in the following:

> Framing is an operation used to define agents (an individual person or a group of persons) who are clearly distinct and dissociated from one another. It also allows for the definition of objects, goods and merchandise which are perfectly identifiable and can be separated (...). Without this framing the states of the world cannot be described and listed and, consequently, the effects of the different conceivable actions cannot be anticipated (Callon 1998, 17).

A framing may, for example, refer to the achievement of actors in establishing a contract between a producer (e.g., a heat utility) and a buyer (e.g., a heat customer). Without defining the role of the actors, the price of the heat to be traded, the conditions of the trade, etc., the heat cannot be produced and sold. Framing the rule of exchange between the two parties is, thus, essential in that it facilitates the detachment and attachment of the heat from the power utility to the customer. The contract delimits, with as little ambiguity as possible, the world in which the trade is to be conducted. As such, framings stabilize the world as they make it knowable and actionable in particular ways.

Callon (1980, 1998) also emphasizes the importance of problem-framing activities. He argues that, when a concern or a problem arises in a socio-technical network, *"protagonists are involved in a never-ending struggle to impose their own definitions and to make sure that their view of how reality should be divided up prevails*." (Callon 1980, 198). He, thus, argues that examining how concerns and uncertainties are framed and translated into problems is of paramount importance. According to Callon (1980), the examination of how a problem is delineated, by whom, and with which material devices, exposes how a situation is made knowable and actionable in particular ways.

This has implications for examining district heating transitions. By approaching problems and concerns as being the result of achievements rather than as pre-given entities, it may be possible to unpack how problems are conceived, framed and displaced by specific groups of actors. It may, thus, enable one to examine how a situation of uncertainty in district heating systems is made actionable. This implies paying attention to the concerns present in the field and to the dynamics through which they are transformed into problems.

Furthermore, as discussed in the above section, material devices are heterogeneous and may make different states of the world visible, i.e., they may *frame* the world in specific ways (Jenle and Pallesen 2017; Stissing, Cashmore, and Elle 2017). For example, Garud, Gehman, and Karnøe (2010) demonstrate how different actors frame nuclear power as "too cheap to meter", a "monumental disaster" or "a sustainable energy resource". The technology itself remains the same, but its framing changes according to who is framing the technology and to which material devices they resort. Therefore, the process of framing does not only refer to a numerical assessment of the world – it also includes judging and moral assessment. To escape the distinction between a mathematic calculation and a judgmental calculation, Cochoy (2002) introduces the notion of "*qualcul"*, which Callon (2017) explains in the following:

> (...) calculation can just as well meet the requirements of the mathematical or algorithmic formulation as it does approach intuition, judgment, the decision process in a situation of uncertainty or, ultimately, withdrawal. With [qualculation] (...) the distance between qualitative judgment and quantitative numerical calculation disappears. [Qualculation] denotes the entanglements between qualitative judgment and quantitative calculations. (Callon 2017, 168, my translation)

In other words, to *qualculate* refers to both the quantitative and the qualitative assessments of a situation, an object, or an operation to be acted upon. The term permits an escape from the dualism of seeing the two as separate.

This may be relevant in the context of district heating transitions because it permits to unpack not only how the numerical applications are made, but also the moral assessments that are made along with these calculations. To put it succinctly, framing is a fragile *qualculative* achievement performed by some actors in the prospect of making specific aspects of goods or situations visible to some other actors, which, in turn, enables them to calculate the world and act accordingly. For the sake of readability, this thesis uses the term *calculation* but it conveys the sense of *qualculation.*

However, Callon (1998) demonstrates that framings always remain precarious; the success of a framing depends on the stability of the outside world (the elements not bracketed), of which all are themselves potential sources of overflows (elements escaping the framing achievement). For example, heat cannot be exchanged between the utility and the heat customers without a pre-existing and stable economic system, regulations, and regulatory institutions, all of which have a specific role to play in the transaction. Additionally, if one of them does not execute its role, the transaction cannot be framed and take place. The crux of the argument is, hence, that the elements that provide solidity to a framing are, at the same time, the elements that can generate overflows. Framings are, thus, always precarious because the sources of overflows are multiple and, therefore, require continuous maintenance. This thus demands that one is sensitive to both the elements which permit a framing to be achieved, and that a framing is always considered a precarious achievement which, despite being momentously successful, always remains subject to overflows and collapse.

3.2.4. HABILITATION AND PROSTHESIS

Scholars attending to the elements providing capacity for action have simultaneously attended to the elements depriving it, such as the inability to take a decision or implement a project. Callon (2008) argues that these incapacities may result from a lack of the necessary equipment – or material devices – to calculate situations. In such situations, Callon (2008) posits that the actors' agencies can be re-shaped in two ways: through prosthesis or through habilitations.

In the prosthesis approach, an actor lacking the capacity to calculate a situation can be 'repaired'. By being granted access to a new tool or new competencies, the actor can be 'equipped' and, henceforth, conduct the calculation. In this situation, the inability to calculate is deemed to belong to the actor, and it is the actor that needs to be adapted if s/he/it is to accomplish its calculation. For example, an energy planner in a situation of uncertainty in terms of whether a specific technology should be implemented, can be 'equipped' with energy modelling software and, thereby, calculate the situation and decide whether to implement the technology under consideration.

In the habilitation approach, it is the environment that is transformed to permit the agent to perform its action. By modifying the actor's environment, the information originally lacking is made accessible to all and at all times. This approach, hence, transforms the calculative agency of not only one actor but many. For example, a heat utility might modify its customers' environment by applying a new heat tariff structure, thereby, enabling all its heat customers to take the decision to consume more or less heat. Callon (2008, 45) continues:

> Prothesis and habilitation are two symmetrical approaches. Both aim to compose an individual agent: the former by acting primarily in the person, the latter by striving to transform the environment. (...) [B]oth compose individual agencies, but according to radically different models. Habilitation shapes an interactive agency and at the same time endows the individual with the capacity to define projects and realize them. By

> contrast, the addition of prostheses extends the individual to enable her to conform to common norms.

Callon (2008) also adds that the two approaches are not necessarily mutually exclusive and may even be complementary in some situations. For example, an energy planner might need both new software (the prothesis) and a new tariff structure (the habilitation) to take a decision about a specific heat strategy. Without one or the other, the actor may not be able to conduct his/her/its action. Habilitation and prothesis approaches may, thus, be used in energy system transitions to equip the actors (customers, heat utilities or energy consultants) in their situation of uncertainty or inability to take a decision.

In conclusion, it appears that being open to the heterogeneity of material devices mobilized in energy transitions, their associations to one another, and the framings they can lead to may allow one to follow the actions, their origins, and their effects unfolding in energy transition systems in a new way. Besides, it may allow one to refine the concept in terms of who can or cannot act, and to detect different approaches for reconfiguring DH utilities or customers equipment in their situation of uncertainty. The following section develops what these concepts from the Sociology of Translation and the Sociology of Markets entail for conceptualizing energy system transitions.

3.3. CONCEPTUALIZING ENERGY SYSTEM TRANSITIONS

The Sociology of Translation and the Sociology of Markets, which I refer to as the socio-technical network approach, provides a conceptual toolbox for analyzing actors, actions, technologies, associations, and the processes of change/stability. It can thus bring new insights into energy system transitions, as summarized in the following.

The socio-technical network approach tends to go beyond the mere analysis of technological changes. Instead of trying to develop and apply neat analytical ordered accounts of the world, as researchers in the field of transition studies have tended to do, authors who apply the socio-technical network approach delve into the messiness of unfolding actions, which means that they remain open to the different sources and effects of change. As the approach applies a flat ontology to the world, technological evolutions are no longer at the forefront of the action and, consequently, they may reveal types of change other than technological. Under this light, energy system transitions are not the result of strategic orchestration and pre-existing themselves (Sovacool 2016; Roberts and Geels 2019), but are emerging by design (Garud, Jain, and Tuertscher 2008).

Furthermore, in contrast to the transition studies literature, where change is conceptualized as being the result of tensions between pre-defined levels (i.e., niches, regimes, landscapes), in the socio-technical network approach, change is conceptualized as a network effect. This implies that any element composing a network can be the source of change, which entails remaining open to the contingencies of how change can be brought about in each *site*, in the very particular circumstances within which the change occurs. Consequently, this implies being attentive to the different concerns, heterogeneous elements, and their associations present in the field.

Furthermore, as each site is made of different elements (space, actors, organizations, time), an energy transition results from the specific circumstances within which the action unfolds. In this light, an energy transition, therefore, can not be compared to another: it is *situated* and specific to the site where it unfolds. This suggests that transitions should be understood as situated network effects and should, therefore, be studied in nearness (Latour 2005).

Besides, authors in the field of transition studies, as they remain somehow distant from the field with historical studies far from the actions, have remained blind to the role of the equipment mobilized by the actors in their situation of uncertainty. Multiple scholars have, however, emphasized the paramount role played by these material devices in regard to the actions they can carry (Callon 1998, Muniesa et. al 2007, Grandclément 2008, Doganova and Eyquem-Renault 2009). Additionally, Sociology of Markets' scholars have emphasized the diversity of material devices existing 'out there', which are diverse in terms of their form, the actions they enable, and what they make visible. Therefore, paying attention to the material devices mobilized by the actors in transitioning process may reveal new insights into how energy transitions unfold. Furthermore, it may also provide richer explanations regarding who and what has agency, instead of pre-defining it (e.g., incumbent, challengers).

The socio-technical network approach may also allow one to break away from the generic understanding of 'energy transition' given in the transition studies literature, in which an energy system transition is a taken for granted concept that refers to a general change in the form or shape in which energy is distributed or consumed between two points in time (Sovacool 2016). In contrast, authors who apply the socio-technical network consider distinctions such as sustainable/unsustainable, true/false, success/failure as network effects and reject pre-given categorizations. This means that the qualification of practitioners in achieving a "sustainable energy system transition", or not, is a situated framing achievement. Consequently, this implies that authors should investigate sustainable energy system transitions without letting common distinctions affect how they look at the field. Analytically speaking, this entails unpacking the elements that are mobilized in the framing activity.

In a few words, the socio-technical network approach conceptualizes 'energy system transition' as a network effect always in the making, whose origins and outcomes can never be pre-defined. In this light, energy system transitions are emergent and situated phenomenon. The particular entanglement of humans and non-humans, materials, technologies, organizations, institutions, etc., are fragile achievements which can always be undone. Altogether, the socio-technical approach enables to move away from the somehow rigid frameworks distant from the action proposed by Transition Studies scholars, and therefore to conceptualize energy system transition under a new light. The methodological implications of applying this socio-technical network approach are developed in the following **Error! Reference source not found.**.

CHAPTER 4. METHODOLOGICAL CONSIDERATIONS

This chapter develops the methodological considerations informing this thesis given the theoretical approach presented in the previous chapter. It connects what has been identified as being relevant to look for based on the theory with the methodology of how to look for it. Therefore, what follows is an account of the gradual solidification of my research objective and approach. Although it presents a somewhat chronological and straightforward development of the research process, it has in fact been a continuous iterative process between the theory, the fieldwork, and the problematization of the research question (Law 2004). This chapter thus presents the methodological choices that I made along the way, which permitted me to formulate my research questions and generate the field materials.

Positioned within the constructivist approach developed in the former chapter, this thesis does not claim to reveal the 'truth' about Greater Copenhagen DH energy transition. Instead, it provides my account of Greater Copenhagen DH transformations and aims to increase knowledge on sustainable energy transitions by following them as they unfold (Latour 2005).

The first section presents the methodological considerations feeding into the thesis. The second presents how Greater Copenhagen, and two specific sites, became objects of study, while the third section discusses how the empirical materials were generated.

4.1. METHODOLOGICAL CONSIDERATIONS WITH THE SOCIO-TECHNICAL NETWORK APPROACH

The socio-technical network approach, with its sensitivity to the role of material devices in equipping the actors, suggests that district heating systems are precarious and situated (socio-technical) networks. This section clarifies what this entails in terms of methodological considerations. It provides answers as to *how* I am going to approach the field and it reveals a strategy for identifying the sites of enquiry.

4.1.1. INQUIRING ABOUT DH 'SUSTAINABLE TRANSITIONS'

Inquiring about energy system transitions *in the making* implies following the action. For that purpose, the Sociology of Translation advocates following the actants *in media res* (Latour 2005), amid their doings, and following the making and unmaking of associations. This means going out into the field and asking the utilities about their work of – and uncertainties about – assembling 'sustainable district heating system transitions'. This implies attending to the particular heterogeneous elements that compose the DH utilities' socio-technical network, as well as their past developments (Kjellberg and Sjögren 2020). This means that, in each explored DH transition site, one must look back in time and trace the evolutions of the elements composing the site. Concretely, it means interviewing the DH utility's practitioners about their present and past specificities, as well as tracing, through documents retrieved at different points in time, the evolutions that have occurred locally.

Advocates of the socio-technical network approach also argue that there is no limit on the number of actants participating in a given action, and that the origins of change/continuity in a DH site can emerge from unexpected places. Therefore, how should one orient one's research in a sea of actants? Where to start and where to end? Callon (1991) argues that the answers lie in the network itself. It is in the continuous analytical moves between the scientific observations and the actants that the answer arises. He explains:

> "The choice of method obeys no epistemological imperative since it is entirely dictated by the state of the network. If the network standardizes itself then one is bound to count and calculate. If it is divergent and reversible, then excessive simplification (and quantification) will betray the state of the network, and it is better just to tell a story! Each actor is relatively unpredictable because any translation is constantly being undone. Here, then, the only faithful – indeed intelligible – method is that of literary description. Such description multiplies points of view to form a polyphonic narrative distributed over as many voices as there are actors, and recovers all relevant details." (Callon 1991, 152)

This quote provides at least three methodological take-aways for this study. First, it calls for being curious and open to the possible associations that energy transitions might engender. The actions unfolding cannot be known in advance; it is only through the iterative movements between the observations and the object of inquiry that the state of the network can be known. This suggests that the researcher should not decide beforehand what matters and what does not in an investigated DH site. In other words, it implies that any assumptions about district heating transitions should be minimized, and instead attention should be paid to the elements constraining/enabling the interviewees in their work. The elements that matter might find their source in the actors' equipment (perhaps new DH meters or a new pipe layout), or they might come from past evolutions (perhaps a municipal disagreement or socio-professional associations).

Second, letting the network decide what matters also implies not judging the veracity of a fact; what is true/false, a success/failure, significant/unimportant must come from the network itself. Concretely, 'sustainability' or 'unimportant' must be conferred by the district heating practitioners themselves. This entails discerning the rationale upon which a fact is based and to, accordingly, inquire about the field in a roundabout way. In practical terms, it means asking an interviewee "How would you characterize your district heating system?" and to then follow the elements of answer. If the interviewee answers that s/he characterizes the system as sustainable since a fuel conversion (for example, a shift from coal to biomass), it entails to follow the framing on which the 'sustainable fuel' hinge.

Lastly, the quote calls for rich descriptions; it is only through detailed and comprehensive descriptions that genuine recognition of the socio-technical network can be found. It thus entails listening to the controversies, the different voices, and the different opinions that co-exist 'out-there'. According to Callon (1991), multiplying the viewpoints is the only way to recover the details of what matters in each investigated instance.

Besides, giving room for what matters in each site may lead to different sets of empirical data. For example, in the first site, what matters may be the organizational structure, whereas in another, it may be a new technology. This, therefore, means that each empirical analysis may have its own elements, dynamic and tone and, consequently, the empirical analyses may differ significantly from one another.

Yet, how should one inquire about the professionals' understandings and work within DH system transitions, as well as the role of the material devices in these sites? And, how should one inquire about the situated concerns and equipment without knowing in advance which actants are present? Although the Sociology of Translation does not provide specific elements for navigating in the field, in his definition of Techno-economic Networks, Callon (1991) identified some characteristic features that can be used. He reduces the heterogeneity of "intermediaries" (referring to 'mediums of actions') into the following four main categories: 1. literary inscriptions (reports, books, laws, articles, etc.); 2. technical artifacts (machines, infrastructure, instruments, etc.); 3. human beings (organizations, individuals, skills, etc.), and 4. money. These four main categories have guided my first investigations and are summarized in the following Table 1.

Table 1: Actants in the DH field according to Callon's categorization (1991)

Literary inscriptions	Regulation, Scenarios, Consultant reports, Municipal Plans
Technical artifacts	Heat production technology (size, type of fuel, capacities, pipes), (smart) meters, heat installations
Human beings	Municipalities, Heat Producers, Heat Distributors, Consumers, Mayors, Directors, Energy Planners, Scientists
Money	Investments, sunk costs, maintenance and operation costs, heat prices, electricity prices, taxation, fuel prices

These elements have enabled me to navigate the field and to generate my account of what seemed to be important in changing the way DH operates, thereby creating some kind of order out of the world's messiness. The four categories of actants proposed by Callon (1991) have permitted me to think about the regulations, technologies, organizations, and money flows present in the DH field in conceptually inspired ways, and to think about the theory with these elements, which helped identify what matters to the field. This mode of reasoning is referred to as being 'abductive', i.e., an interpretation of the field guided by theory and strengthened by new observations (Alvesson and Sköldberg 2018).

Given the theoretical considerations developed in the previous chapter, the following section develops how to inquire about, specifically, the material devices involved in district heating transitions.

4.1.2. INQUIRING ABOUT 'MATERIAL DEVICES' IN DH TRANSITIONS

As seen in the previous chapter, material devices lie at the heart of action; "*They act or make others acts*." (Muniesa et al. 2007, 2). Material devices are, accordingly, privileged entry points for understanding energy transitions in the making. Being attentive to the material devices that are mobilized or created in transitioning processes, and the capacity for action they permit, is thus one of the analytical keys chosen in this thesis.

As highlighted by the socio-technical network approach, each site has its own composing elements and, therefore, two sites of district heating transitions may mobilize two different sets of material devices. In the field of DH, material devices may refer to elements such as prices, doors, formulas, or business models. However, given the diversity of material devices and their distributiveness, it is impossible (and also undesirable) to encompass all the devices contributing to the transitions of energy systems. According to Callon (1991), it is the network itself that must dictate what is important to the researcher.

However, what is known from the Danish DH and energy system literature is that energy scenarios (Sperling, Hvelplund, and Mathiesen 2011), heat planning strategies (Chittum and Østergaard 2014), regulations (Lund and Münster 2006), and business models (Lygnerud, Wheatcroft, and Wynn 2019) are some of the material devices present in the field. These devices may enable different actions; energy scenarios may enable, to a greater extent, the calculation of technology futures, regulations to compel a given future, and business models to facilitate investments. Although material devices can be characterized as serving different purposes (calculating, inscribing, regulating), these different functions can be difficult to uphold as devices are mobilized in different contexts. Hence, the aim is not to classify material devices, but to rather remain open to their diversity in shape and career.

However, inquiring about the practitioners' tools has some limits. As emphasized by Callon (2008, 38), "*the subject is not external to the devices*". Rather, the practitioner and his/her equipment are entangled and mutually adjusted. The devices are familiar objects, and, accordingly, they may be difficult to perceive. In other words, the actors may not notice their own material devices and, consequently, not mention them. For example, an energy planner at a DH utility may consider a business model or a smart meter "mundane" tools because they are integral to professional work and, therefore, they may not mention them. The fact that material devices are discrete entities thus highlights the expediency of inquiring about the field in a roundabout way. Concretely, it implies that a DH utility employee should be asked questions such as "what tool did you use to calculate the feasibility of this technology? And is it the same tool as this other actor's tool?"

Besides, scholars from the field of the sociology of markets have demonstrated that material devices are selective and can be combined with other devices (Muniesa et al. 2007). Consequently, this suggests that interviewees should be asked about what a device can make visible, to whom, and whether the device is assisted by others. Concretely, it entails asking "What do these new Smart Meters enable you to see?", or "Does this new heat bill require coordination with another tool or actor to function?" These types of questions allow one to detect both the heterogeneity of devices involved in the situated DH transitions and to also observe their effects.

Altogether, these elements provide the answers to *how* to inquire about the Danish DH field. The following section provides the answer to *which* sites should be explored.

4.2. TOWARD A CASE STUDY

This section discusses how I conducted an initial investigation into the Danish DH field. It explains how, in order to identify DH transitioning sites, I conducted an initial round of interviews with professionals, and how this process led me to narrow my research field to the Greater Copenhagen area, and to then select case studies. Greater Copenhagen appeared to be an experimental network where different DH transitions were unfolding, which led me to identify three different sites (locations) within Greater Copenhagen, and two different sights (observation points).

4.2.1. APPROACHING THE DANISH DISTRICT HEATING FIELD: AN INITIAL INVESTIGATION

In Denmark, there are about 400 district heating utilities of varying sizes, with different ownership models, heat customers and heat production units. Considering this diversity, I chose to follow the utilities that were recognized in the field for being particularly engaged in a transitioning process. The intention was to be led to sites where transitioning phenomena could be witnessed most vividly.

As I intended to be driven by the field, I followed what the practitioners themselves defined as ‘pioneering’ district heating utilities. Therefore, I followed the professionals’ newspapers and reports and identified the utilities that were recognized as “special” in terms of their innovative approach to decarbonizing their facilities. One of the first cases that was identified was HOFOR, Copenhagen district heating utility. The utility was involved in a demonstration project in which the practitioners were developing “flexible heat customers”, i.e., they were using buildings as heat storages and were, for that purpose, taking control of the customers’ heat supply at specific times. The objective was to develop a low-temperature DH grid and reduce peak loads. As the project was gaining national recognition when I started my investigation, I decided to interview the leader of the project, Kristian Honoré. He suggested that I interviewed two of his colleagues with whom I could explore further aspects of the utility’s efforts towards a low carbon future.

The second interview was conducted with the district heating utility Brønderslev, in Northern Jutland. The utility had won the Danish District Heating Association Oscar in 2018 (when I started my investigation) because of its innovative “Smart Energy Concept”, which combined state-of-the-art technologies (Dansk Fjernvarme 2018). I decided to investigate the reasons and circumstances that had led to this recognition and I, therefore, interviewed the utility’s director.

I subsequently used each new interview to identify where to go next – a method often referred to as ‘snowball sampling’ (Mason 2002; Bryman 2016). For example, the interview with Brønderslev DH utility led me to interview Århus (the second largest city in Denmark) DH utility. Århus utility had recently designed a new heat market for the producers based on real-time heat price mechanisms. The interview with Århus DH utility led me to interview Skanderborg utility, which neighbors Århus and was recognized by Århus utility as being the first to modify its customers’ heat tariff structure.

Besides interviewing DH utilities, I also conducted an interview with an energy consultant to get a sense of how the field has evolved, as well as with a heat energy scholar to get a better understanding of district heating systems which, considering my social science background, was initially quite limited. During this initial investigation, which was carried out from the fall of 2018 to the fall of 2019, I conducted ten interviews, which are summarized in Table 2, below.

Table 2: Interviews carried out during the preliminary investigation of the Danish DH field.

	Names	**Company**	**Role**	**Date**
1	Kristian Honoré	Copenhagen DH utility (HOFOR)	Project Leader Nordhavn	11/09/18
2	Thorkil B. B. Neergaard	Brønderslev DH utility	Director	24/09/19

3	Frederik E. Lynge	HOFOR utility	Product Developer	29/10/18
4	Søren Dycke Madsen	CONCITO	Senior Consultant	30/10/18
5	Bjarne Munk Jensen	Århus DH utility	Director	08/03/19
6	Peter Jensen	Skanderborg DH utility	Director	15/03/19
7	Jan Hindsbo and Michal B. Thomsen	CTR (Copenhagen DH transmission utility)	Vice-Director and Operations manager	19/03/19
8	Christine E. Sandersen	HOFOR DH utility (HOFOR)	Energy Planner	14/05/19
9	Per Heiselberg	Aalborg University	Building Energy Scholar	21/04/19
10	Lasse Sørensen	Århus DH utility	Business Developer Manager	05/09/19

This process narrowed down the number of DH utilities to be investigated from 400 to 20 “known” pioneers in the field. During the same period, I also attended economic and technical conferences about DH to be able to understand what the professionals were talking about, what the concerns were, and on what rationale the successful stories relied upon.

This initial investigation led me to realize that the pioneers had become pioneers for various reasons. The conditions and circumstances that had resulted in a utility being considered a pioneer in one site were not comparable to another. For example, the size and number of inhabitants in Copenhagen enabled HOFOR, the utility, to use the building mass to increase the flexibility of the DH system. In comparison, in Brønderslev, the building mass and heat demand are relatively limited. In contrast, whereas Copenhagen utility explained that they had very limited space to implement new and greener production technologies, Brønderslev had plenty of space and could, therefore, expand solar panels and other large production technologies, which enabled them to develop the so-called ‘Smart Energy System’. Or again, Århus DH’s strategy was influenced by another specific circumstance: it owns both the regional heat transmission and distribution systems, which meant it had agency in implementing heat mechanisms that HOFOR, Brønderslev or Skanderborg-Hørning could not. However, Skanderborg-Hørning utility, because of the relatively small size of the town, was able to engage in a new discussion with its customers in order to reduce their heat consumption, and then implement a new incentivized heat tariff structure.

In short, it appeared that the means of enacting energy system transitions were emerging from diverse and site-specific elements. The size of the network, the urban fabric, the utility's customers' observations, as well as their main infrastructural challenges, appeared leading the utilities in assembling radically different "sustainable energy system" approaches, as summarized in the following Table 3.

Table 3: Summary of the first four district heating sites explored.

	Skanderborg Utility	Brønderslev Utility	HOFOR utility (Cph)	Århus Utility
URBAN FABRIC	Low buildings, parcel housing, spread out	Low buildings, parcel housing, spread out	Tall buildings, high density, hospitals and institutions, mostly old buildings	Tall buildings, high density, hospitals and institutions, mostly old buildings
RESPONSIBLE FOR	Distribution	Distribution and entire production	Distribution and some production	Transmission, Distribution, and some production
MAIN CHALLENGE	The heat losses in the pipes	The loss of a main production subsidy	The peak load hours	The peak load hours
OBSERVATIONS ABOUT THE CUSTOMERS	Customers can react to price signals	Heat is invisible to the customers	Customers are the janitors of the buildings. Heat is invisible to the customers	Customers are the buildings janitors. Heat is invisible to the customers
APPROACH	Redesigning customers' heat tariffs'	Developing a "Smart Energy System"	Flexible heat buildings	Redesigning the heat production market

Furthermore, because district heating is a geographically bounded form of energy, the organizations, economic dimensions, social relations, etc., were all distinct from one site to another. In other words, the materiality of DH and the specificities of each socio-technical network in which the transitions were unfolding called for in-depth analyses to identify the concerns and devices that mattered in each particular site. Consequently, considering the timeframe and scope of this thesis, this initial investigation led me to move away from the multiple identified cases to focus on one site of analysis.

4.2.2. NARROWING THE NUMBER OF SITES

Considering the need to focus on one site of analysis, I decided to analyze one large-scale district heating network. In my preliminary interviews, practitioners had explained that the concerns present in large-scale DH systems were similar to the ones commonly encountered by district heating utilities, although the size of the (socio-technological) network appeared to render them considerably more significant – and therefore, traceable – than in other places. A top manager of one of the district heating transmission companies in Copenhagen for example relates:

> My problem is that my peak load capacity corresponds to the capacity used to cover Esbjerg's [5th largest city in Denmark] heat demand. (…) It is not necessarily more complex; it is just much bigger (…) Everything is amplified!

Greater Copenhagen was identified by the practitioners as a site where transitioning processes could be vividly witnessed. Moreover, the professional literature pointed to Greater Copenhagen DH as a pioneering and experimenting site. Concretely, HOFOR (Copenhagen DH utility) was designated as being particularly innovative for its 'Energy Laboratories' (i.e., the "flexible heat buildings" in Nordhavn and the "heat communities" in Sydhavn, Pedersen 2014; Jørgensen et al. 2019). The nearby municipal DH utility, Høje-Taastrup, was recognized for having implemented the first heat pump system which could supply both cooling and heating in Denmark (Pedersen 2018), while Albertslund DH utility, based in Albertslund (another municipality close to Copenhagen) was recognized for being a first mover towards a "4th generation DH" (*DBDH* 2015).

Besides, I already had a sense of the regional infrastructure as I had carried out four interviews with local practitioners. Therefore, I decided to focus on Greater Copenhagen district heating system. Furthermore, as it appeared that different transitions were unfolding within this large system, I chose to zoom in on two specific cases and delve into their unfolding associations, as well as investigate where Greater Copenhagen's socio-technical network was coming from. Examining the latter was a prerequisite for understanding the former (Asdal 2012). Consequently, I had to assemble sites (locations) with different sights (observation points).

4.2.3. ASSEMBLING SITE/SIGHTS

As argued in the previous chapter, understanding the messiness and the past evolution of a socio-technical network are both prerequisites for investigating ongoing sustainable energy transitions (Callon 1986; Asdal 2012). To this end, recent socio-technical inquiries have emphasized the benefit of pairing sites with sights (Labussière and Nadaï 2018). The researchers bring together different case studies (sites) with different observation points (sights). Similarly, Stirling (2019) and Iuel-Stissing (et al., forthcoming) argue for taking a "worm's" and a "bird's" eye view when investigating the emergence of socio-technical objects. While the former allows one to observe the messiness of sites, the latter facilitates an examination of the wider (in time and space) dynamics of change and continuity.

The coupling of the "bird's" and "worm's" eye views thus appears to enable one to address both the situatedness of the socio-technical changes and to trace its past evolution. Whereas the former allows one to inquire about the stabilized and authorized accounts of the past messiness, the latter facilitates an inquiry into the messiness of the ongoing processes. In other words, the bird's eye view paves the way for an understanding of the worm's eye view. It must here be noted that the two sights are not equivalent to the "micro" and "macro" levels. Informed by the Sociology of Translation's flat ontology principle (Callon 1986), the distinction is not a matter of different levels of realities. Rather, the sights concern where to stand as an inquirer (Muniesa et al. 2017, 17).

Applying this coupling of sites and sights to my research objective resulted in opening the inquiry with a longitudinal exploration of Greater Copenhagen DH transitions (**Error! Reference source not found.**). This, then, laid the foundations for worm's e ye examinations of two sites in Greater Copenhagen, namely, the implementation of the first regional Thermal Energy Storage (**Error! Reference source not found.**), and t he transformation of Albertslund's municipal DH utility from a traditional to a "4 generation" DH grid (**Error! Reference source not found.**). As district heating's l ow-carbon future is about identifying synergies along the energy chain (Lund et al. 2014), these two cases would allow me to conduct an inquiry into transition processes in the distribution and the consumption part of the energy system and, consequently, to understand energy system transitions across the supply chain. The identification of these two cases and the motivations for studying them are further developed in the following two sub-sections.

4.2.3.1 Implementing the first common Thermal Energy Storage

The establishment of the first large-scale pit Thermal Energy Storage (TES) in Greater Copenhagen has been underway since 2014 and is expected to be operational in the fall of 2021. It is one of the regional projects involved in transitioning the DH grid to carbon neutrality. The project has often been depicted in the professional media as an 'easy technology'; it was "*a hole to dig in the ground with a plastic liner and an insulating lid*" (*Sn.Dk* 2019). The 'hole' was said to enable the production of cheaper heat and to assist the regional energy transition by enabling CHP plants to integrate more wind power into the heating grid. The project was mentioned several times during my preliminary interviews as a pioneering enterprise and has been repeatedly mentioned in the professional newspapers (Wittrup 2015; *Sn.Dk* 2019).

However, Bertelsen and Petersen (2017) had indicated that the project was more complex than depicted in the professional media. The project involved a total of five producers, two transmission companies, one distribution company, and two energy consultancy companies. The transmission companies experienced difficulties establishing contracts with the producers and building a viable operational and business model for the technology. It appeared as if the technology had quickly moved from being 'easy' to 'very complex to implement'. It is this paradox that led me to choose this case as a site of energy transition *in the making.*

As Bertelsen and Petersen (2017) had investigated the case in 2017-2018, they had already conducted a total of six interviews with the involved actors. They granted me access to their interview transcripts, and we agreed to keep following the project in collaboration (see Bertelsen et al., n.d.).

4.2.3.2 The case of a transitioning municipal DH utility: Albertslund Forsyning

Albertslund is a municipality within Greater Copenhagen and is, as such, part of the regional DH socio-technical network. The municipality has been framed by the academic literature as being a pioneering site several times. For example, Elle (2001) recognizes the municipality as being "*outstanding with respect to Local Agenda 21 in Denmark*" (p.162), Sperling, Hvelplund and Mathiesen (2011, 1341) describe it as a "*frontrunner municipality*" in terms of energy strategy, Agger and Sørensen (2014, 192) suggest it has "*a strong tradition of citizen involvement*", and more recently, Lygnerud (2019, 6) describes it as being one of the "*forerunners in terms of the [district heating] low-temperature technology shift*".

Albertslund Forsyning, the DH utility, is also represented in the newspapers as being an energy frontrunner (Pedersen 2011; Høg and Moos 2016), and it also perceives itself as such. For example, one of the utility's energy consultants relates the following:

> There are 400 district heating utilities in Denmark. If you are asked to name the 20 most exciting ones where something is happening, then we are in these 20.

Furthermore, Albertslund Forsyning is one of 26 utilities in Greater Copenhagen that do not produce heat and are only responsible for municipal distribution, which suggests that the utility can only maneuver with respect to other actors. Furthermore, the municipality was established in the 1970s, which allows one to retrace its historical development from a defined point in time. Therefore, all of the aforementioned factors oriented me towards choosing Albertslund DH utility as a site of investigation.

4.2.4. SIGHTS/SITES OVERVIEW

Figure 1 summarizes my approach to tracing district heating transition sites in Greater Copenhagen. I have combined a 'bird's eye view' analysis, which examines Greater Copenhagen DH socio-technical network with two 'worm's eye view' analyses, which examine the TES and Albertslund Forsyning, as discussed in the following.

It must be noted that the delimitation of the different socio-technical networks is not fixed or pre-defined. The illustration has only the representational purpose of indicating my observation points and the sites of analysis. The different colors and shapes representing Greater Copenhagen in the bird's eye view represent the three main temporal configurations of concerns, regulations, and actors when analyzing the Greater Copenhagen DH socio-technical network. These boundaries of the socio-technical network in these three time periods are not fixed as the system continuously evolves.

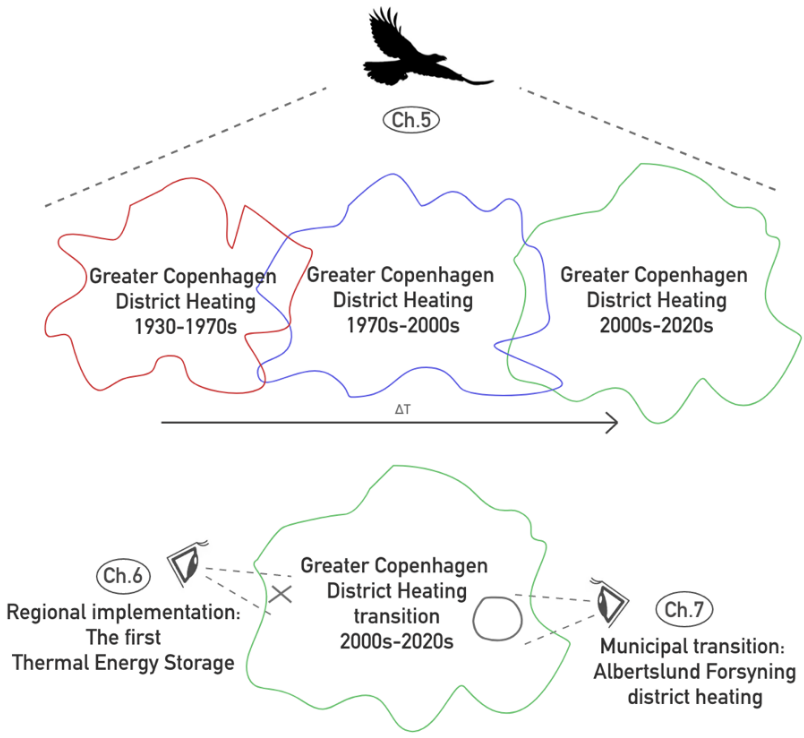

Figure 1: Illustration of the investigated sites from different sights.

The analysis of Greater Copenhagen was conducted at a distance from the unfolding actions – it is a retrospective analysis of the transition processes. The empirical materials are based on reports and newspapers collected at specific points in time, as well as interviews with professionals who 'were there'. Altogether, this provides an aggregated account of what the field remembers has happened and is, as such, the authorized history emerging from the field (Asdal 2012).

The analyses of the TES and Albertslund Forsyning were carried out amid the transition processes. The empirical materials were based on contemporary reports and newspapers, as well as interviews with professionals. Historical accounts of the sites were also retrieved to identify from which past developments the sites have emerged, thereby enabling an identification of their implications for the ongoing transitioning processes. These analyzes trace the associations between the concerns, material devices, technologies, and the different actors in their efforts to transform the district heating system towards their own definitions of sustainability. This entails attending to the nitty-gritty details of their actions and being sensitive to the contradictory voices existing in the field (Latour 2005; Law 2009).

The composition of these different sites and sights results in three empirical chapters with their respective narrative flows, temporalities, actants, and actions as what matters in one site differs from another. For example, the presence of business models and energy scenarios is significant in the TES site (Chapter 6), whereas it is secondary in the analysis of Greater Copenhagen (Chapter 5) and Albertslund Forsyning (Chapter 7). Also, the urban fabric is of great importance in the analysis of Albertslund Forsyning, whereas it is absent from the two other sites.

Finally, having identified how to start the investigation and what to look for, the question of “when to stop?” still remained. The answer to that question lies at the nexus of the empirical materials and of my research timeline. If data can practically be collected endlessly, the repetition of the empirical data is one indicator that suggests the data collection process should be stopped (Czarniawska 2014). Another, and pragmatic, reason for stopping is the deadline for submitting the Ph.D.

4.3. GENERATING EMPIRICAL DATA

Empirical data was collected through literary sources (e.g., documents, reports and newspapers) as developed in the first sub-section, as well as through interviews, as developed in the second sub-section.

4.3.1. READING THE FIELD

Documents, reports, and newspapers were used in all three analytical chapters. They were central to building the foundation of the interviews and were also used to complement the information gathered during the interviews.

Newspapers

Newspapers made an essential contribution to getting a sense of the field. I approached the media as a mirror of concerns, i.e., as material where concerns are explicated and made visible (Marres and Moats 2015).

From the early days of the study, I subscribed to several professional newspapers to get a sense of what was happening in the field; daily newsletters from the Danish District Heating Association (da. *Dansk Fjernvarme*), Energy-Supply.dk (covering the Danish energy and supply sector), and the engineering newspaper Ing.dk (where professionals post blogs and debate). These sources introduced me to the field and kept me informed about on-going DH debates. This daily feed made an essential contribution to targeting data collection; it enabled the identification of pioneering sites, controversies, and discussed regulations, and it allowed me to read about the different actors' interests.

I complemented these searches with the media archive, Infomedia.dk, which enabled me to follow unfolding controversies and events over time. The fragmented materials, which were crosschecked and assembled, facilitated the creation of a general account of the unfolding events and what they looked like when they were occurring (Asdal 2012; Marres 2012).

Documents and reports

The identification of Greater Copenhagen and the two sites of analysis narrowed the (media and) document search. I was able to identify which actors had participated in which projects and which role they had, and as such retrieve their reports which could then be used both as background for the interviews and in the analyses.

Nevertheless, I encountered two main challenges during this data collection process. One was limited access to historical papers about the specific developments in district heating in Denmark and Greater Copenhagen. The number of books and papers concerned with these developments is rather limited and they relate the same authorized history; authorized in the sense that the documents relate the same stabilized history and authorized in the sense of "authorship"; the two main books that relate the development of the energy and DH sector in Denmark were published by the Danish District Heating Association and the energy producer, Ørsted, which both have their own respective political agendas. These main contributions were supplemented by documents retrieved from the media archive, Infomedia.dk, and from danmarkshistorien.dk, a website administered by the Department of History at Århus University.

The second challenge was the confidential character of the contracts, prices, and energy analyses made and exchanged by the different parties in Copenhagen. It was not possible to get hold of confidential information, which occulted some of the negotiation processes and financial aspects of the investments carried out.

Overall, I intended to approach the newspapers and reports with a constructivist approach, which is to say to approach them as textual devices actively participating in the construction of knowledge about district heating and energy transitions. The objective was to avoid judging or defining the truthfulness of the content of the documents, but to rather continuously question the rationale upon which they were built.

4.3.2. CONDUCTING INTERVIEWS

From the Fall of 2018 to Easter 2020, a total of 21 semi-structured interviews (Bryman 2016) were conducted with directors and energy planners of large and small DH utilities, with transmission companies, energy consultants (from think tanks and energy consultancies), energy researchers, CHP producers, the Danish Energy Regulatory Authority, and citizens (cf. Appendix A for a list of the interviewees).

Additionally, as part of another research project (IREMB[3]), I conducted 6 interviews with directors of DH utilities at Easter in 2018, and I had access to another 6 interview transcripts from Bertelsen and Petersen's study from 2017-2018 concerning the Thermal Energy Storage. Whilst I primarily used the latter set of interviews to guide and narrow my interviews, some quotes are used directly in the thesis.

To begin with, I was what I would today describe as a candid outsider in the sense that I knew little about the field and asked rather ingenuous questions, which often triggered interesting and clear explanations from the interviewees. I also stressed my social science background so that the interviewees would not take my understanding of their technical and operational expertise for granted. I asked questions regarding the utility's historical developments, the elements that have triggered changes, relationships with other actors/organizations/institutions, as well as technical limitations and economic issues. Appendix B provides an example of a semi-structured interview guideline conducted with a top manager from a transmission utility. In addition, email communications were exchanged to follow up on some of the interviews when necessary. Due to the outbreak of the Covid-19 pandemic in March 2019, some of the interviews were carried out online. Overall, the respondents were happy to be interviewed, and some of them were enthusiastic about sharing their knowledge and passion for district heating.

I also carried out one field observation; after an interview with a member of Albertslund Municipality, I was invited to a "User Group Meeting" (da. *Brugergruppenmøde)*, where I took notes about the content and the form of the meeting and made a sketch of the setting.

I conducted the first few interviews in English, but decided it was better to conduct the remainder in Danish. One of the reasons for doing so was the feeling that the interviewees would be more comfortable using their terms, for which some could not find equivalent English terms (such as the '*Hvile-i-sig-selv'*, a non-profit principle specific to Danish district heating regulations). Another reason was that my level of Danish proficiency had become high enough to carry out the interviews in Danish. If I had thought this would be a barrier and that I would get lost in translation (both

[3] 'Innovative Re-making of Markets and Business Models for a Renewable Energy System Based upon Wind Power' led by Professor Peter Karnøe.

technically and lexically), the opposite turned out to be the case; it pushed the interviewees to explain complicated matters simply.

The 21 interviews were transcribed in their entirety, and Danish speaking colleagues were asked to translate utterances that I could not understand or transcribe myself. My approach was iterative in that I moved between the transcripts, the other empirical material, my theoretical framework, and the methods that guided my reading and analysis. It was also an abductive process, one that "*alternates between (previous) theory and empirical facts (or clues) whereby both are successively reinterpreted in the light of each other*" (Alvesson and Sköldberg 2018, 5). This process gradually led me to discover the material devices that equipped the actors in the field; the socio-technical network approach and New Economic Sociology contributions informed my readings of the transcripts. It enabled me to discern the heterogeneity of the devices mobilized by the actors in the field, as well as to discover the roles and effects of these devices.

I only translated the citations used in the analysis from Danish to English. When I settled on the citations I wanted to use, I wrote back to the interviewees and attached the interview transcript in which the quotes had been underlined. I asked for the interviewees' permission to use the underlined quotes and, subsequently, received their approval. I wish to stress that my translation choices may have decreased the eloquence of the interviewees, which is entirely the result of my work of putting their words into English.

4.4. WHAT IS THIS A CASE OF?

What does this scientific account say about the world? What can this composition of theoretical, methodological, and empirical materials claim about the making of energy system transitions? An initial attempt to answer this question may involve posing another one: what does this scientific account *not* say about the world? Well, it does not give a recipe for how to investigate and implement 'sustainable energy system transitions', and it does not claim to provide an omniscient truth about Greater Copenhagen DH transformations. This thesis is not simply a reproduction of an existing 'out there' reality. As Latour (1999) argues, his account of the forest-savanna is not an exact representation of the unfolding phenomena observed, but rather another circulating reference of it. He explains:

> You can now look at a map of Brazil in an atlas, at the area around Boa Vista, but not for a *resemblance* between the map and the site whose story I have been recounting. This whole tired question of the correspondence between words and the world stems from a simple confusion between epistemology and the history of art. We have taken science for realist painting, imagining that it made an exact copy of the world. The sciences do something else entirely – paintings too, for that matter. (...) I can never

> verify the resemblance between my mind and the world, but I can, if I pay the price, *extend* the chain of transformations wherever verified reference circulates through constant substitutions (Latour 1999, 79).

Likewise, this account is a circulating reference of Greater Copenhagen DH transition. It is ‘only’ a nuanced account of a DH transition *in the making* assisted by material devices.

This account contributes to making district heating more present in the social science literature. It enlarges the rigid and distant frame of analysis often imposed on actors and energy transitions identified in the Literature Review, Chapter 2. By attending to the relationships between the involved entities, this account rather reveals the messiness and nearness of energy transitions. Attending to the details of transition processes will enable us to understand what ‘sustainable energy system transitions’ are made of and will allow us to go beyond the predominant focus on technology evolutions (Köhler et al. 2019).

This account also makes a contribution to the Sociology of Translation and Market literature. Whilst the Sociology of Translation has been used for many types of investigation (Blok, Farías, and Roberts 2020), it has scarcely been used to study district heating transitions (Köhler et al. 2019). Therefore, this account contributes to making the technology and process more present in this literature. Additionally, the Sociology of Markets has a predominant focus on economization and marketization processes, and has left other processes (such as energy transitions) uninvestigated (Asdal 2014; Muniesa et al. 2017). Therefore, this account also contributes to expanding the Sociology of Markets field of study.

Furthermore, in keeping with McFall’s (2009, 278) argument “(...) *the virtue of the sociology of market attachment lies not in telling us about consumption generally – about that we already know plenty – but in telling us about the distributed and material character of market processes specifically”*. By analogy, the virtue of my approach is not to inform about energy transitions in general, but to bring their materiality and distributiveness to the forefront. By remaining open to the sources and effects of actions, this account provides a new reading of an already studied phenomenon.

CHAPTER 5. GREATER COPENHAGEN'S HEAT SOCIO-TECHNICAL NETWORK

This chapter examines, from a "bird's eye" view, the developments in Greater Copenhagen's heat socio-technical network. Because it is necessary to comprehend the past before it is possible to understand the present, this chapter begins with an historical analysis of heat provision from the 1950s to the 1980s. The section shows how concerns for security of supply in the 1970s brought about the emergence of the regional heat socio-technical network, which contributed to the gradual intertwinement of material, technical, and social elements.

Since this thesis is more focused on the examination of transitions in the making, greater emphasis is placed on the most recent developments rather than those of the past. Accordingly, the first section of this chapter is relatively brief in comparison to the succeeding ones. The second section examines the transitions induced by the liberalization of the electricity sector in Greater Copenhagen. This section reveals how the practitioners created new material devices to adapt to the changes while striving to maintain the regional daily heat load dispatch. The third and final section examines how carbon neutrality concerns appeared in the region and induced the mobilization of new material devices in order to transform the regional heat production.

5.1. SECURITY OF SUPPLY AND EMERGENCE OF A REGIONAL DH INFRASTRUCTURE

In Denmark in the 1950s and 60s, there were no energy planning procedures or a Minister of Energy. Energy planning was conducted without centralized governance or regulative authorities, and the Danish Government mostly relied on local public stakeholders and low oil prices in the Middle East to implement energy developments (Rüdiger 2011). By 1972, Denmark's oil consumption accounted for 92% of the total gross energy consumption (Rüdiger 2011; DEA 2016a).

However, with the oil embargo in 1973, the price of oil increased by nearly 400%, and Denmark was recognized as being one of the countries that had been most seriously hit by the crisis (Hadjilambrinos 2000; Rüdiger 2011). Historical accounts refer to this crisis as the start of a new Danish Energy Policy era (Frederiksen 2018; Rüdiger 2014; Mortensen 2018). From this point on, the Danish Government became involved in energy planning and established the Danish Energy Agency (DEA) in 1976 (DEA 2016a; Sovacool 2013).

The DEA had the following two priorities: fuel diversification and energy savings. District heating (DH) received increasing attention from the DEA, which soon made it one of the infrastructural pillars of energy self-reliance. The establishment of municipal DH grids was seen by the Government as a way of solving the oil crisis, increasing the energy efficiency of the country, whilst at the same time ensuring the security of heat supply to the inhabitants and solving the waste issue (Skov and Petersen 2007; Rüdiger 2011; DEA 2016a).

In 1979, the DEA signed the Heat Supply Act, the first law initiating district heating regulations in Denmark. This piece of regulation is considered to be the foundation for the developments of heat supply in Denmark (H. C. Mortensen and Overgaard 1992; Rüdiger 2011). The Heat Supply Act made DH to be a governance object on its own, with its set of rules, market, and organizational structure (Karnøe and Jensen 2018).

The Act tasked the municipal authorities with developing local heat infrastructure; they were instructed to map their heat demand, report it to the DEA, and carry out the project developments once validated. The DEA also stipulated the use of '*socioeconomic calculations'* to govern investment decisions. These calculations excluded fuel taxes and externalities (such as air pollution) but included major externalities, assumptions about future energy developments, and specific technical properties (DEA 2016a). Furthermore, DH projects had to be conducted under the '*rest upon itself*' principle (da. "*hvile-i-sig-selv"*); no profit could be made from the production of and trade in heat. Besides these economic regulations, the Act also established mandatory connection areas (da. *tilslutningspligt*), stipulating that properties belonging to these areas be connected to the collective heat supply system (LBK nr 64 of 21/01/2019).

In Greater Copenhagen, sparse and unconnected district heating infrastructure was already present in the city and the surrounding municipalities (Skov and Petersen 2007; Rüdiger 2011). The socioeconomic calculations and the heat planning performed by the municipalities resulted in a DEA decree, which stipulated that one large DH transmission network ought to connect the 16 surrounding municipalities, as well as the construction of a 1,100 MW CHP plant to ensure regional security of supply (DEA 2016a, 16).

Funding and governing the decreed transmission infrastructure consequently required the 16 regional municipalities to identify a regional DH transmission utility and its ownership model. The transmission utility had the role of developing and operating the regional grid in the long and short term. This called the municipalities to define and agree upon whom was legitimate to endorse this new role (*Politiken* 1981). Therefore, negotiations began in the early 1980s and a municipal East/West divide quickly emerged: Copenhagen Municipality in the East versus Albertslund and its surrounding municipalities in the West (Skov and Petersen 2007; VEKS 2020b).

Given its status as the nation's capital and the largest city in the region, Copenhagen Municipality saw itself as a legitimate candidate for the regional transmission utility (Rüdiger 2011). The municipality proposed that it should be the main owner of the DH infrastructure and that the remaining shares should be split between the surrounding municipalities. By owning the greatest share of the infrastructure, Copenhagen Municipality would have had the most agency in steering regional DH developments.

However, this did not please the municipality of Albertslund and its surrounding Western municipalities. Led by Albertslund's politically active and social democrat Mayor[4], Finn Aaberg, the Western municipalities considered Copenhagen Municipality unsuitable precisely because it already had too much agency over other infrastructure (such as the water supply), and past experiences had made them skeptical (Int. Gullev and Stobbe). Furthermore, the Western municipalities had a political desire to carry out "*large societal tasks*" themselves (Finn Aaberg in VEKS 2020) and they perceived the heat development plans that had been proposed by Copenhagen Municipality to be at their expense[5].

The negotiation process lasted for 3 years and it was eventually settled in 1982. Copenhagen and the Western municipalities decided to solve the East/West divide by creating two transmission utilities instead of one. Lars Gullev, who was employed at the Western transmission company VEKS a few years after its creation, relates:

> We took the decision we often take in Denmark when two parties cannot agree; that is, to ensure that both parties get something. So, the 1,100MW CHP plant that was to be built got divided into two CHPs: one is Avedøre's block 1 in [the West], and the other is Amagerværk's block 3 [in the East]. And in that way, a natural boundary was made between the two transmission companies. (…) So, we had Copenhagen, Frederiksberg, Gladsaxe, Gentofte and Tårnby in the East, and all the rebels who were together in the West. (Int. Gullev, my translation)

The 12 Western and the 5 Eastern municipalities thus established their own transmission companies, VEKS in the West, and CTR in the East. Concretely, this means that VEKS and CTR have their respective owners, budgets, contracts, operation, and maintenance strategies and, therefore, different heat prices (Int. Gullev and Stobbe). It also means that the owners of the transmission companies are also the customers; the municipalities own either a share of VEKS or a share of CTR and buy heat from one or the other through their respective municipal district heating utilities.

[4] To which we come back to in Chapter 7.

[5] Copenhagen wanted to build the new 1,100 MWh CHP plant in the East of Copenhagen (in Amager), but the Western municipalities were afraid that the heat would never reach them (VEKS 2019; *Politiken* 1981),

Figure 2 illustrates the two transmission companies' ownership model, and Figure 3 is a map of the transmission network.

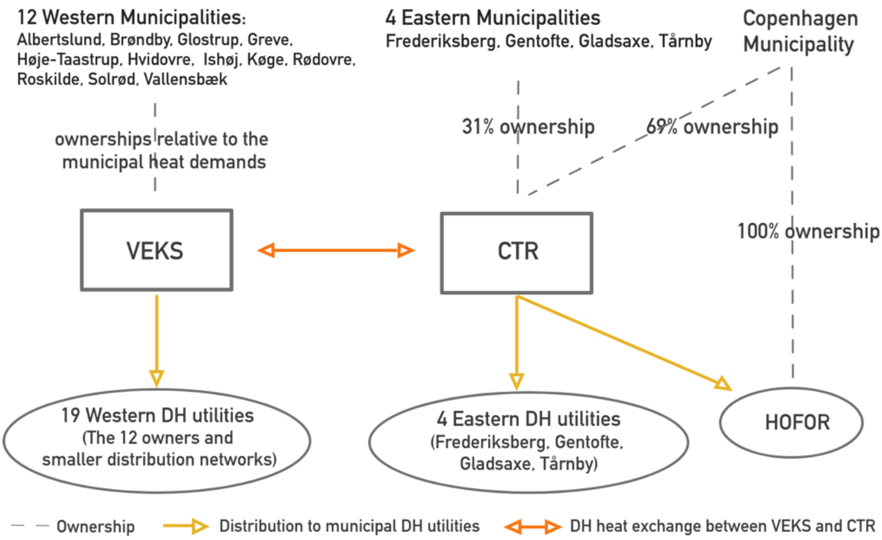

Figure 2: CTR and VEKS ownerships.

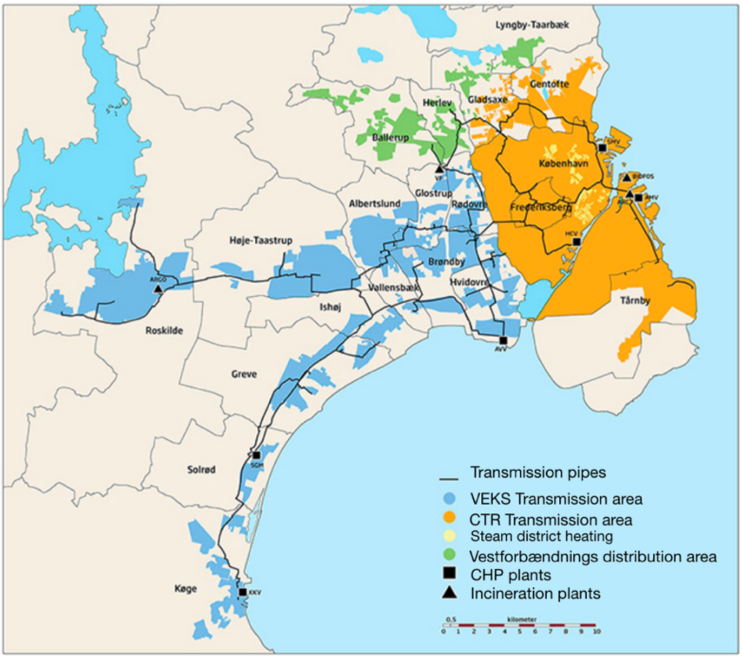

Figure 3: CTR and VEKS transmission network. (Varmelast 2020b)

Another implication of the establishment of the regional infrastructure is that the surrounding municipal district heating utilities had to concede the use of their existing production units to the transmission companies. Being the transmission utilities, VEKS and CTR assumed responsibility for distributing the heat regionally and deciding which heating units should produce when and how much. Consequently, from this point on, the municipal district heating utilities were only responsible for distributing the heat from the transmission pipes to their end customers.

Furthermore, as illustrated by the orange arrow in Figure 2, and by the representation of the transmission pipes in the second, CTR and VEKS are physically connected despite being owned by different municipalities. According to the DEA's calculations, the region had to establish regional transmission infrastructure to avoid suboptimal investments. As such, the two transmission networks had to be connected and exchange heat. Thus, the heat produced and transmitted by VEKS can be sent to CTR's customers and vice versa. This physical configuration entailed that the two companies were built upon the prerequisite of collaborating and ensuring the regional heat planning. Their efficiency depended upon one another: the better their collaboration, the more efficient the infrastructure. Since their establishment in 1982, VEKS and CTR have been meeting weekly to ensure an efficient security of supply (Int. Hindsbo).

From sparse district heating networks in the 1960s and 70s, about 90% of Greater Copenhagen had been connected to DH by the 1990s (Rüdiger 2011). The transmission network connected a total of 17 DH utilities, radically transforming the way heating was produced and distributed in the region. According to CTR's current vice director, Jan Hindsbo, these developments have created a "*tradition of working together*". He explains that CTR and VEKS meet and coordinate activities on a weekly basis, and continues:

> The main question is why don't we combine VEKS and CTR today? (...) But the value of CTR is about maybe 3 billion, that the customers have paid during the years (...) and VEKS value is maybe something like 4 billion, and they have many different municipal owners. (...) So if you are to (...) combine [CTR and VEKS] ownerships, some of the municipalities will need to pay the other ones. It is a lot of money, and it is very difficult to divide it because in a sense they are not "real". We have activities, pipes in the ground, we have plants, etc. (Int. Hindsbo, my translation)

The stranded assets, the complex ownership models, the materials (the pipes, the water flows, the CHP plants) have made merging the two companies inherently complicated, despite their regular interactions. In addition, the price signals and regulations provided by the DEA (being non-profit, the socio-economic calculations, the mandatory connection, etc.) seem to have formed the foundation for the development of Copenhagen's DH infrastructure and all future DH projects. These price signals and regulations are the governance instruments, created on a rationality of heat security, from there on controlling the Danish heat provision (Karnøe and Jensen 2018).

Therefore, these past developments seem to have set the conditions upon which collective action can emerge in stone. They have crystallized in an intertwined socio-technical network of organizations, materials, regulatory instruments, which, as discussed in the following sections, will have an influence on the future regional developments and their increasing complexity.

5.2. LIBERALIZATION OF THE ELECTRICTY SECTOR

In the 1990s and 2000s, concern about the efficiency of energy sectors emerged both in Europe and world-wide (Ossandón and Ureta 2019). Based on the neoliberal assumptions that market deregulation and de-bundling of the production-supply chain would lead to the optimization of energy sectors, a new consensus gradually crystallized, reducing the authority of governments, and increasing the role of markets as policy instruments (C. Frankel, Ossandón, and Pallesen 2019). The European Commission and its member states then gradually initiated the liberalization of the electricity sector.

In Denmark, these directives led to the establishment of new national legislation in 1999, which stimulated, among others, an amendment to the Danish Electricity Act written after the oil crisis in 1976. From this point on, Combined Heat and Power (CHP) plants, which produce both electricity and heat, were regulated by two different regulations: the for-profit electricity sector and the non-profit district heating sector. This duality complicated the operation of the CHP plants and the DH utilities, who had to adapt to new contracts and heat production forms with the newly established commercial actors (U. G. Frederiksen 2012; H. B. Mortensen 2018). The liberalization also initiated the unbundling of the electrical supply chain, thereby provoking ownership change.

The following sub-sections discuss the transformation of Greater Copenhagen DH's socio-technical network as a result of the liberalization of the electricity sector in Denmark. The sub-sections also examine how new material devices were mobilized to repair the modifications resulting from the liberalization.

The first section analyzes the consequences that changing the ownership of Combined Heat and Power (CHP) plants had on the DH socio-technical network. It also discusses the attempt made by the regional heat producers and the transmission utilities (VEKS and CTR) to reconfigure the socio-technical network by creating three intertwined material devices, namely Varmelast, the heat contracts, and spreadsheets, which I categorize as being respectively administrative, contractual, and, physical. The second section discusses the significance of social ties for the good performance of the material devices and the social effects resulting from and through these three devices.

5.2.1. NEW FORMS OF OWNERSHIP AND EMERGENCE OF ASYMMETRIES

5.2.1.1 Destabilization

In Copenhagen, 8 CPH units were built between 1920 and 1999 by two municipally owned energy companies, namely, København Energi (Copenhagen energy company) and SK Energi (a power plant company in Zealand). At that time, the district heating and electricity sectors were considered as natural monopolies and were regulated according to the same principles: there was no market competition between the energy producers, who were not allowed to generate profits from energy sales, and the same owner could own an entire chain of energy production and distribution. Lars Gullev, who works at the transmission company VEKS, relates:

> At that time, [the transmission companies] had contracts with each CHP block. [The transmission companies] would first run the cheapest block, and then the next cheapest block, and so on, until we had the settled heat prices. There was no competition between the different production facilities. (Int. Gullev, my translation)

At that time, energy producers traded both electricity and heat according to the lowest marginal cost of each production unit, which were known to everyone. The CHP producers coordinated the regional heat load dispatch according to the lowest marginal cost, and they could therefore ensure an economically optimal load distribution for the heat and electricity production in the metropolitan area (Varmelast 2020a).

However, in the 2000s, the deregulation of the electricity market began and Denmark joined the newly established European electricity market, Nordpool (OECD 2000). The electricity production chain had to be dismantled: production, transmission, distribution, and retail were to be operated by different owners. As a consequence of these regulatory changes, København Energi and SK Energi were compelled to sell their CHP plants. Bjarne Lillethorup, who worked as a contract manager at Energi E2 at that time, relates:

> In 2000, the power plant part of Københavns Energi and SK Energi Power Plants merged into one company named "Energi E2". Only Københavns Energi's power plants were included in the fusion, as the district heating part and the electricity distribution part continued to be Københavns Energi's responsibility. This means that Energi E2 owned all the combined heat and power plants in Greater Copenhagen area. The daily organization of heat production at combined heat and power plants was carried out by Energi E2, as we owned all the combined heat and power plants. (Int. Lillethorup, my translation)

As Bjarne Lillethorup relates, København Energi was split and became Energi E2, which was split again a couple of years later in 2007 and was sold for competition purposes to two incoming market players: DONG Energy and Vattenfall (Rüdiger 2011).

Due to the competition on the electricity market, the energy producers were no longer allowed to disclose their marginal costs or coordinate the economically optimal heat load distribution of the region. Lars Gullev relates that it led to concern for the two DH transmission companies:

> We couldn't leave it to DONG and Vattenfall to agree on how to share the market between themselves. Otherwise, they could have just set a bar and decided... (Int. Gullev, my translation)

The transmission utilities were concerned that DONG and Vattenfall would have too much discretion when it came to steering the heat production – they could produce electricity (and simultaneously heat) regardless of the lowest marginal costs in the region. However, Bjarne Lillethorup suggests that the producers were also concerned about the new situation:

> It is in our interests to produce (electricity and heat) together. If you do not achieve to distribute the heat, then you are in a bad position. (Int. Lillethorup, my translation)

It appears that the CHP plant owners were also concerned about not being able to optimize their heat and electricity production together, as it would undermine their electricity and heat production finances. The interviews suggest that there were concerns and uncertainties on both the production and transmission side. And, on a market with only two commercial producers and two transmission heat utilities, Kamma E. Holm (currently director of the transmission company CTR) explains that "*either everyone has power or no one has power*" and continues:

> I cannot choose a producer other than [the two commercial ones]. So, in that sense, they have power. On the other hand, they also need to make sure that I do not get too angry. So, in other words, we are dependent upon each other. (Int. Holm, my translation)

Unlike electricity or gas, district heating is a geographically bounded form of energy, and can only be used locally, which results in the situation of dependency described by Kamma E. Holm. The buyers need to be sure that the producers will keep on producing, while the producers need to be sure that the buyers will continue to buy.

In other words, there was a symmetrical tension between the heat buyers and producers who became dependent on one another. Furthermore, both were dissatisfied with the new situation, which did not ensure an economically optimal heat load production and distribution. For this reason, in 2008, the producers and buyers agreed to establish a heat system operator: Varmelast.

5.2.1.2 Varmelast

Varmelast is not a legal entity; it is a collaboration between VEKS, CTR, and København Energi (Copenhagen's DH utility) and has been in operation since 2008. Varmelast was established to "*ensure an economically optimal load distribution of both electricity and heat*" at the regional level (Varmelast 2020b). Literally translated, Varmelast means "Heat load" in English. The name was chosen to mirror the name and function of "Energinet", the newly created national transmission system operator for electricity (Int. Gullev and Stobbe). The reason why HOFOR was also involved in the establishment of Varmelast is because of the size of Copenhagen's heat demand; the utility delivers heat to approximately 600,000 customers, which represents the largest share of heat demand in the metropolitan area.

Having to meet heat demand and marginal costs

The liberalization of the electricity sector rendered the CHP plants marginal costs (i.e., the costs of producing one additional unit of heat) confidential, preventing the transmission companies from buying heat according to the lowest available marginal costs. Varmelast was meant to solve this issue.

Varmelast creates a sort of neutral "buffer" between the heat demand of VEKS, CTR, and København Energi (renamed HOFOR in 2013), on one side, and the CHP producers' marginal costs of heat production, on the other. Therefore, Varmelast facilitates the encounter of the heat demand and the supply regionally without disclosing information from one side to another. Figure 4, below, illustrates the 'buffer' created by Varmelast.

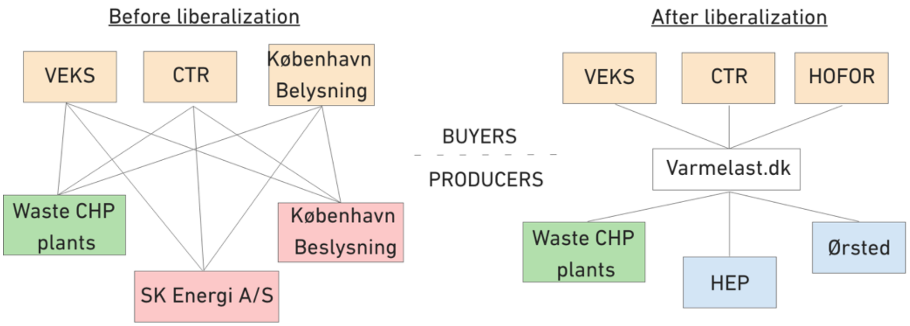

Figure 4: Lowest marginal costs configuration before and after the liberalization of the electricity sector. HEP stands for 'HOFOR Energy Production' and 'Ørsted' is the other commercial producer. Made by the author.

Varmelast creates a confidential space where heat demand and marginal costs can be collected. However, considering the diversity of fuels (waste, oil, coal, biomass), the respective earnings on the electricity market, the respective costs (maintenance and operation), and the different prices and charges (paid waste, subsidized biomass, taxes on electricity conversion to heat, oil, and coal market prices), aggregating the costs from lowest to highest meant that the actors had to define what was "*economically optimal*" for the entire system. For this reason, Varmelast also had to aggregate and order the marginal costs and, therefore, decided to establish what could be categorized as an administrative device.

Aggregating the marginal costs

Once Varmelast has aggregated the daily prognostics of the producers' marginal heat costs and the DH utilities' heat demand forecasts, Varmelast still needs to sort the marginal costs from lowest to highest to establish an "*economically optimal heat load dispatch*" (Varmelast 2020b). This entails defining and calculating the "*economically optimal*" heat load for the region and, therefore, Varmelast established an administrative device to allocate the different levels of demands and supply according to a number of defined priority mechanisms.

The first priority mechanism stems from governmental waste management regulations. The "Waste Duty" (da. *Affaldspligt*) stipulates that incineration plants must burn municipal waste continuously throughout the year to prevent the accumulation of waste. As expressed by the director of CTR Kamma E. Holm, "*[incineration plants] actually solve another problem; waste is not burnt for the sake of the heat consumption, but for the sake of getting rid of waste*." (Int. Holm, my translation). To ensure that the incineration plants can fulfill their duty, Varmelast must firstly aggregate their marginal heat costs. The productions of the three incineration plants in the region are consequently the first to be aggregated by Varmelast[6].

Once this has been done, the device can administer the marginal costs of the other existing heat productions, i.e., the CHP plants and the peak production units. CHP plants have high investment costs but relatively low marginal costs, whereas peak load productions have low investment costs but relatively high marginal costs. Therefore, the CHP plants are the second production units whose marginal costs are calculated and aggregated by Varmelast, while the peak-load productions come last. Figure 5, below, illustrates how the heat productions are administered by Varmelast.

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[6] As incineration plants are paid by the municipalities for burning their waste, whereas regular CHP plants have to pay for their fuel, waste incinerations plants represent the cheapest form of heat production (Int. Holm).

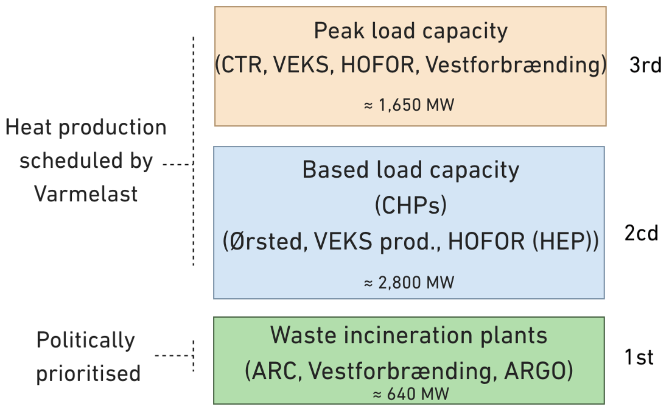

Figure 5: Administrative device for the heat load dispatch in Greater Copenhagen[7].

However, Varmelast does more than just aggregate the marginal costs: it also schedules the heat production units. As the collaboration is meant to ensure economically optimal dispatch of both electricity and heat, it must take into consideration the CHP producers' bids on the liberalized electricity market. Jonathan Thordal, an energy planner at Varmelast, relates:

> We take into account the [heat producers'] wishes when we make a plan. When I make a [daily] heat plan, I usually call Ørsted and ask: "How does this daily heat plan look to you?". Then they might say: "Not so good, it would be better like this". Then I call HEP and do the same. And this is the reason why Varmelast exists. It permits the total production to be optimal without the competitors knowing each other's costs. They typically say [the plan] is fine with them, but otherwise they say "We would rather have it like this" and then we find a compromise. (Int. Thordal, my translation)

In other words, Varmelast aggregates the marginal costs of all the production units and then calculates a compromise with the heat producers to schedule the optimal heat and electricity load dispatch. About 90% of the time, the heat load dispatch administrated by Varmelast is considered to "*make the cake bigger*", which means that 90% of the time, the compromise calculated and scheduled by Varmelast is to the

[7] *Made by the author after Int. with Gullev and Stobbe, and data retrieved from Forsyningtilsynet. Vestforbrænding, ARC, and ARGO are the three waste incineration plants in Greater Copenhagen. HOFOR is the current name of København Energi, HEP refers to HOFOR Energy Production, which bought Amagerværket from Vattenfall in 2014. The name Ørsted replaced DONG in 2017.*

advantage of both the producers and heat utilities (Int. Lillethorup; Thordal; Holm 2020).

When the production from the waste incineration plants and the commercial producers does not meet the heat demand (which can happen on cold winter days or if technical issues occur), peak load productions (owned respectively by HOFOR, CTR, VEKS and the waste incineration plant Vestforbrænding) are aggregated and scheduled according to their lowest marginal costs. The schedule is adjusted six times a day in case of unexpected events (technical issues, hydraulic bottlenecks, higher/lower heat demand, which are further discussed in the following section 5.2.1.4).

In conclusion, Varmelast first aggregates demand/supply in one 'buffer' (cf. Figure 4) and then produces a schedule to ensure the daily heat load dispatch of Greater Copenhagen. The scheduling can be described as being the result of an 'administrative' device in the sense that it permits to organize the regional heat production on the basis of specified ordering mechanisms. The decision regarding what is "*economically optimal for the region*" is based on a combination of political prioritization and compromise seeking between Varmelast and the heat producers. This configuration ensures both an optimal co-production of electricity and heat to the producers, and the access to the lowest marginal costs available to the heat utilities.

Whereas Varmelast administers the heat load dispatch based on the producers' marginal costs, it does not establish the heat prices. For this purpose, the practitioners rely upon another device.

5.2.1.3 Heat contracts

Marginal heat costs and heat prices are two different things; marginal costs are the costs of producing one additional unit of heat, whereas heat prices are the result of negotiations between producers and buyers. Heat prices typically encompass marginal costs, a proportion of annual costs (such as investments, operation, maintenance, etc.), and variable costs (such as fuel costs). Therefore, heat prices and heat costs have different values. Lars Gullev, VEKS' director, explains:

> Varmelast does not have any contracts. It administers the heat based on the marginal production costs. It has, in fact, nothing to do with the sales / purchase agreements. (…) The actual heating bill, the price, not the cost but the price, if we are VEKS, then we have different contracts with [the CHP producers]. (Int. Gullev, my translation)

The heat costs of the different production units are known by the producers and Varmelast but not by VEKS, CTR, and HOFOR. Similarly, only VEKS, CTR, HOFOR, and the producers know their respective heat prices, which are not known by Varmelast. Morten Stobbe, the vice-director at VEKS, continues to explain:

> We have contracts that directly steer our settlement conditions. There is also a part of the production at Ørsted's[8] CHP plant 'Avedøvre' that goes to CTR, and that is their individual contracts. (...) So, that way we have a price with Ørsted (...), and also one with ARGO and one with Vestforbrænding. (Int. Stobbe, my translation)

The heat prices are settled in contracts, which are the result of negotiations between the producers and the heat utilities. The heat contracts are not new devices, but they have been re-written in the aftermath of the liberalization of the electricity sector. The following Figure 6 illustrates the contractual agreements signed between the heat producers and heat utilities.

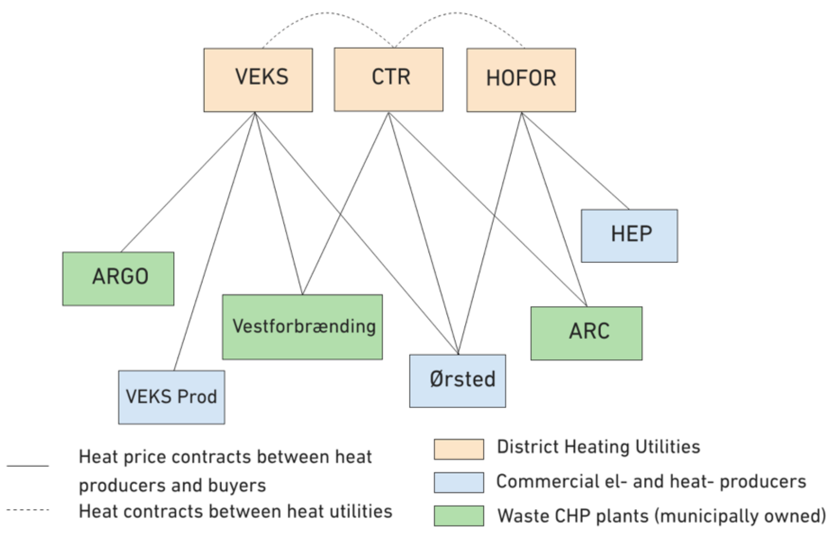

Figure 6: Contracts between the energy producers and the DH companies in Greater Copenhagen. Made by the author.

VEKS, CTR, and HOFOR purchase their heat according to the heat load dispatch administered by Varmelast, but the heat prices are settled in the respective contracts, which are hundreds of pages in length and establish how the two parties are to conduct their heat trades for the subsequent 20-30 years.

However, as briefly mentioned above, the daily schedule established by Varmelast is then updated six times a day on the basis of technical limitations in the district heating network and the producers' heat production costs. Consequently, the heat load

[8] DONG's new name since 2017.

dispatch scheduled by Varmelast may not occur exactly as planned. Therefore, the administrative and contractual devices must be backed up by yet another device.

5.2.1.4 Spreadsheets ensuring delivery and payment

As indicated by the dotted lines in Figure 6, VEKS, CTR, and HOFOR also have heat contracts with each other. The reason is that Varmelast's administrative dispatch does not necessarily materialize in the actual heat flows. Two things can happen. First, the scheduled heat production unit may encounter a technical problem and may not be able to deliver the heat it was supposed to. Second, the spatial discrepancy between heat productions (mostly decentralized) and heat demand (mostly concentrated in Copenhagen) may lead to bottlenecks. Jonathan S. Thordal, an energy planner at Varmelast, explains:

> There are hydraulic constraints. The CHP plant Avedøverværket is for example limited at Damhus Lake. We also have hydraulic constraints (…) from Copenhagen to around Gentofte. Sometimes the hydraulic pressure is so high that utilities have to run local peak production instead. So, it is not unusual for a CHP plant to produce less for a few hours, and (…) to consequently have local peak load productions to run a lot. (Int. Thordal, my translation)

The heat load dispatch scheduled by Varmelast may not be physically feasible, which can result in a discrepancy between the planned and the actual physical heat load dispatch. In such a situation, the use of (high marginal costs) local peak production may be required despite the availability of cheaper base-load production. In such a case, "*it may well be that, in the real world, for the current day, in the current hour, the heat is coming from a completely different place [than planned]"* (Int. Stobbe, my translation).

For this reason, CTR, VEKS, and HOFOR also need to mobilize "*very large spreadsheets"* (Int. Stobbe, my translation) to do data processing and to fix the discrepancy between the planned and the actual heat dispatch. These spreadsheets can be defined as calculative devices given their numerical form and the calculative agency that they provide the heat utilities – feeding into the heat contracts, the spreadsheets ensure that the heat being paid corresponds to the heat that is actually distributed.

5.2.1.5 Summary: from collective concern to an intertwinement of material devices

The liberalization of the electricity sector in the 2000s established new trade dynamics between the heat producers and the heat utilities. Whereas it was no longer certain that the utilities would obtain the lowest marginal heat costs available, it was no longer certain that the CHP producers would be able to sell all their heat. Therefore, both of their socio-technical networks were destabilized and in a state of uncertainty. For this reason, continuing to produce and sell heat regionally on a daily basis became a collective concern. The practitioners, in their attempt to restabilize their networks, initiated the collaboration Varmelast.

The collaboration has established what the practitioners referred to as a "neutral" calculative space, which enables the heat demand and supply to be balanced on a daily basis. Varmelast uses an administrative device to schedule the heat load dispatch based on specific prioritization mechanisms. Furthermore, in order to actually produce and distribute the heat, a contractual and a calculative device are also required. Bilateral contractual devices facilitate the economic trades between the heat producers and heat utilities. The contracts define the 'rules of exchange' between the actors. The spreadsheets are calculative devices that resolve any potential discrepancies between the planned and the actual heat load dispatch.

The administrative, contractual, and calculative devices are all intertwined and have been contributing, each in their own way and through their entanglement, to the daily heat load dispatch of Greater Copenhagen since 2008. The following section discusses how the success of these devices is also contingent on the socio-professional relations produced in and through the socio-technical network.

5.2.2. IMPORTANCE OF THE SOCIO-PROFESSIONAL NETWORK

The following sections discuss the origins and effects of the social dynamics emerging in the Greater Copenhagen heat (socio-technical) network. They examine how the social relations that exist between the practitioners in the metropolitan area are shaped by and shaping the network in which they exist, and how these social relations are significant for the operation of the three aforementioned devices.

The first section examines the origins and effects of a shared array of methods, concepts, and ways of thinking, which prevail amongst Greater Copenhagen heat professionals. The second section examines how the successful operation of the aforementioned devices is contingent on this shared understanding.

5.2.2.1 The Heat Planners' social network

Denmark is a relatively small country, and, as a result, only a limited number of educational institutions offer a specialized education in energy planning, energy modeling, and/or energy savings. The main Danish engineering professional union IDA lists fewer than five universities that offer an energy-related education (IDA.dk 2020). Therefore, many of the professionals working in the Danish DH sector have been through the same or similar educational programs. Of the interviewed informants, Lars Gullev (VEKS director), Astrid Birnbaum (Høje-Taastrup Forsyning director, cf. following **Error! Reference source not found.**), and Jonathan S. Thordal (

employed at Varmelast) were all educated at DTU[1]. Furthermore, Morten Stobbe (VEKS vice-director) and employees from Albertslund Forsyning's Energy Team (cf. **Error! Reference source not found.**) both studied Energy Planning at Aalborg U niversity. Even though this is a small sample, it suggests that there are a limited number of educational backgrounds feeding into the Danish DH professional sector. This implies that employees have learned the same or similar tools, models, and skills, which tends to lead to a shared framework of reference in terms of the norms and understandings of the sector (Kreiner 1993; Lygnerud 2019), and contributes to the establishment of 'professional codes', i.e. similar standards and ethics (DiMaggio and Powell 1983; Frankel 1989).

Additionally, despite the fact that Greater Copenhagen is a large metropolitan area, the number of utilities and companies working with DH is relatively limited. There is only one DH utility per municipality (accounting for 19 in the metropolitan area) and only a limited number of energy consultancy companies in the region (IDA.dk 2020). Therefore, it is quite likely that DH professionals will move from one of these organizations to another in the course of their careers. For example, Morten Stobbe has been DH supply director at HOFOR but is now vice-director at VEKS. Similarly, Astrid Birnbaum has been employed at HOFOR (and is a former colleague of Morten Stobbe) but is now the director of Høje-Taastrup Forsyning, where Uffe Schleiss (who we hear from the following Chapter 6) moved to after working at VEKS. These professional dynamics tend to reinforce a shared professional frame of reference as well as the creation of a professional 'community' (Hannan and Freeman 1977; DiMaggio and Powell 1983; Lygnerud 2019; Meilvang 2020). Based on these observations, it appears that the regional DH professionals are familiar with one another's ways of working and that they share similar formal and informal codes.

Additionally, the sector is governed by the rule of being non-profit (da. '*hvile-i-sig-selv*') and "*for the benefit of society"*(Karnøe and Jensen 2018; Varmelast 2020b). These formal rules, originating from a concern to ensure security of supply at low costs in 1976, may have played a standardizing role and facilitated the coordination of actions between engineers and heat planners (Meilvang 2020). It appears as if these rules have gradually become embedded in the informal set of norms, strengthening not only the convergence of the organizational strategies but also a sense of commitment of the professionals, who, in the course of their careers, may have been working on the same infrastructure, albeit at different organizations, but with a shared aim of delivering secure and affordable heat to households.

Furthermore, the 19 municipal district heating utilities connected to the transmission grid meet regularly to steer and coordinate actions both in the short and long-term. There are also smaller steering groups and meetings between companies, to discuss the role of different technologies and negotiate specific futures. For example, Jonathan S. Thordal, employed at Varmelast, relates:

> There are various forums. We also meet with HEP [HOFOR Energy Production], and we also meet with Ørsted. There we typically discuss operation. But we also have other forums where we gather with CTR, HOFOR and VEKS, and where we for example discuss how a particular technology should be used. (Int. Thordal, my translation)

Presumably, these regular interactions serve to strengthen the socio-professional relations between the DH professionals in the region. Furthermore, the professionals also meet in other ways, such as events organized by the Danish District Heating Association, the Danish Energy Agency, or more informally at events such as the "Energitræf", which is held annually by the consultancy company EA Energianalyse[9]. At this event, the company invites its professional network for free drinks and food on a Friday from 16:00 onwards, to which "everyone goes".

These public and private meetings are important as they actively shape the field (Garud 2008). The formal debates and informal drinks are the forums where associations are negotiated and where relations between different organizations and professionals are established. They organize and constitute the field by provoking the establishment of socio-professional relations (Lampel and Meyer 2008).

All of the above suggests that the professionals meet regularly at private and public events and at formal and informal meetings, and that they work on the same infrastructure with a shared understanding of the norms, tools, and social responsibility, the result being that they tend to be committed to the Greater Copenhagen district heating they work with. In turn, this suggests that socio-professional relations are an inherent part of constructing the Copenhagen DH network. The following section shows that these shared professional norms represent the cornerstone of maintaining Varmelast, and the Greater Copenhagen heat socio-technical network.

5.2.2.2 The importance of trust

As mentioned above, Varmelast is not a jurisdictional entity – it is not a legal company but a collaboration. The three initiators of Varmelast (VEKS, CTR, and HOFOR[10]) decided to share its administration so that each of them would have their own employees working at Varmelast. Therefore, HOFOR has one employee working in Varmelast, while CTR has three and VEKS has one (Int. Thordal). The reason why CTR has three employees, and not one like VEKS and HOFOR, is to mirror the ownership and investment shares of the three companies in the collaboration.

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[9] A company which we return to in Chapter 6.

[10] Named København Energi at the time.

However, having employees from VEKS, CTR, and HOFOR administering Varmelast means that these employees do know the marginal costs of the heat production units when scheduling the daily heat load dispatch, despite the point of the collaboration being that the marginal costs would not be revealed to the heat utilities. Therefore, the collaboration stipulates that the employees from VEKS, CTR, and HOFOR who work at Varmelast cannot reveal the confidential information they receive from the heat producers to their mother companies. In practical terms, when Jonathan S. Thordal "*make[s] a heating plan at 10h that tells Ørsted and HEP when their CHP blocks should produce*", he has confidential information about the producers' marginal costs, which he is not allowed to share with his own colleagues at HOFOR.

Also, a Chairman for Varmelast is elected from one of the three mother companies and rotates every two years. This implies that the Chairman has access to information that s/he is not allowed to share with her/his colleagues. This is, for example, illustrated by the following exchange between VEKS' director and vice-director Lars Gullev and Morten Stobbe:

> Lars Gullev: Morten Stobbe is on the Varmelast steering group [as chairman], where I do not sit. I am only involved when the producers are also involved, when there are some joint meetings where I take care of the production's interests. And it works. If one has high morals, it can work.
>
> Morten Stobbe: And we do!

As Lars Gullev puts it, it takes "high morals", for Varmelast to function. This suggests that the shared understanding about what ought to be done and by whom is a key element of the Varmelast operation. This is also something that Kamma E. Holm (CTR director) emphasizes in the following:

> Varmelast is deeply dependent upon the trust that Varmelast is neutral. And, consequently, there are many confidentiality boundaries, also internally in CTR, between who is employed at CTR and who is employed at Varmelast. There are simply different levels of confidentiality, and they also sit physically in different places than the rest of the department. So, there are in that way some boundaries. (Int. Holm, my translation)

Here she also adds that Varmelast's operation is facilitated by the physical separation of the employees. These physical boundaries presumably limit the risk of disclosures. Morten Stobbe also recounts that "*it may be necessary for competing power plant companies to invite one another over, for them to see that one has separated, physically as well, with doors, etc*." the people who steer Varmelast from the people who operate the CHP blocks.

Therefore, the successful operation of Varmelast is based on trust between the companies' employees that they will not disclose information from one department to another. They all know how the information flows between the companies, and they trust each other to not break these information channels. And this trust is also physically assisted by separated office locations, doors, etc.

5.2.3. GREATER COPENHAGEN, A TRANSITION ASSISTED BY INTERTWINED DEVICES

To wrap-up, the creation of a European electricity market in the 2000s resulted in an asymmetry between the heat producers and utilities. The heat producers' marginal costs became confidential, thereby impeding an economically optimal heat and electricity load dispatch; it was not certain that the producers would optimize their cogeneration of heat and electricity, while it was not certain that the heat utilities would be secure the lowest marginal costs available. The empirical data suggests that this situation was unsatisfactory for all parties involved.

Caught in this situation, CTR, VEKS, and HOFOR decided to collaborate and established Varmelast. Although it is modeled after the liberalized electricity market (instead of organizing next-day trades, Varmelast organizes next-day schedules), Varmelast is not a market; it is a collaborative agreement providing a secure space for the confidential information to converge. Varmelast administers "*an economically optimal load distribution of both electricity and heat"* by using an administrative and a physical device.

Varmelast's administrative and physical devices

Varmelast's scheduling device for the regional heat load dispatch is a combination of political concerns (waste management) and negotiations (compromises between Varmelast and the heat producers). It can be considered as an administrative device which is based on the producers' marginal costs. Both the producers and the buyers delegate the responsibility of establishing the most optimal heat load dispatch to Varmelast, and both support Varmelast in finding the most optimal production compromise. In other words, the administrative device establishes the "rules of exchange" between the parties.

However, for the administrative device to perform its role, Varmelast relies on a physical location. The collaboration is manned by employees from HOFOR and the two transmission companies. A separate physical location allows them to manage the risk of commercial litigation, which may otherwise arise, potentially undermining the rules of exchange. To this end, the doors, rooms, and the separate locations help to create a calculative space where information converges and cannot escape. The operation of Varmelast is contingent on these physical measures, without which the risk of information disclosure would be much greater, thereby threatening the heat load dispatch.

The physical devices are one of the elements that allow HOFOR, VEKS, and CTR to collaborate and to learn about each other's positions and, consequently, generate trust. It appears that the trust and the physical space are co-emergent and reinforce one another; Varmelast could not operate without the trust, and the trust is both a source and a consequence of the physical devices.

Bilateral Heat Contracts: calculative and inscriptive device

Varmelast administers the schedule of the heat load dispatch but does not set in motion the heat trades between the heat buyers (CTR, VEKS, and HOFOR) and the heat producers (the waste incineration plants and the private CHP plants). To enable the heat trades, the heat utilities and the heat producers have to rely upon a second device: the bilateral heat contracts, which are the result of negotiations between the buyers and the producers. These devices are a combination of calculations and literary inscriptions: they are written utterances of negotiations, which calculate the socio-technical trades to occur between the producers and the buyers. By attempting to define all the possible technical situations of the different production units, these contractual devices frame, with as little ambiguity as possible, the rules of exchange between the involved parties. The devices are not "new" in the sense that they have been present since the first heat trades, but their content has been reworked as a consequence of the new neoliberal economic reality of the (socio-technical) network.

The contractual devices delineate the modalities of exchange in the short and long-term, which, in turn, reduces uncertainty and renders the future more manageable. The contracts attempt to frame the actors (the companies and the technologies) and make them relatively stable. This, in turn, appears to ensure that their coordination is long-lasting and helps to sustain the regional (socio-technical) network. Therefore, the contracts equip the buyers and the producers with a shared source of 'calculativeness' (Callon 1998) and establish a future within which the actors exist, settling a form of commitment to one another.

Varmelast's administrative device, which schedules the heat production, and the contractual device between the producers and heat utilities are co-dependent: the former cannot administer the heat load dispatch if the latter does not settle the heat prices, and the latter cannot permit the commercial trade if the former does not administer the schedule of the heat load dispatch. Their interdependency is necessary to orchestrate 'the optimal' heat (and electricity) generation and transmission in Greater Copenhagen.

Spreadsheets: the "patching" calculative device

However, these two devices are still insufficient for enabling the daily heat distribution. Varmelast's administrative device schedules the regional production units based on the assumption that the technical components of the DH system will do their job and it ignores the likelihood of breakdowns. Thus, technical failures or bottlenecks, effects of the physical properties that are not taken into account by the prioritization mechanisms of the administrative device, can create a discrepancy between the scheduled and the actual physical heat dispatch. In other words, Varmelast's administration of what is 'optimal' for the region is incomplete as it does not address the material properties of the technical components which, in turn, generates discrepancies or 'overflows' (Callon 1998).

To address the failure of the administrative device, the heat utilities and the heat producers resort to yet another device, i.e., the spreadsheets, which recalculate, post factum, the heat flows which have actually been dispatched. Therefore, the spreadsheets can be considered a 'patching' calculative device as they facilitate the identification of discrepancies between what has been planned and what has been executed. The results of the calculations feed directly into the heat contracts previously discussed and are part of the rules of exchange. It could thus be argued that the spreadsheets are calculative devices equipping the actors in stabilizing the heat dispatch (socio-technical) configuration.

Stabilizing the regional socio-technical network with devices

Overall, it appears that the heat producers and heat utilities have produced devices to maintain the regional heat provision based on marginal heat costs. Each device enables a specific capacity to act, and it appears that the stability of the socio-technical network is a function of the devices' intertwinement. The administrative, contractual and calculative devices are interdependent and rely on one another to operate. The absence or modification of one of these four devices would adversely affect the stability on which the regional heat load dispatch depends. In other words, the configuration of the socio-technical network has been transformed through the practitioners' work of maintaining the regional heat provision as it was known.

In addition, these devices are contingent on the presence of socio-professional relations. These relations, facilitated by a multiplicity of physical devices (e.g., separate offices, doors, etc.), appear to generate trust as an effect of the network in which they exist. It appears that, through the years, the socio-professional network has evolved and tightened, thus enabling the devices to fulfill their functions. The following section investigates how this complex intertwinement of materials, economic, and social ties is currently addressing the climate concerns in Greater Copenhagen.

5.3. CLIMATE CHANGE AND REACHING CARBON NEUTRALITY IN GREATER COPENHAGEN

In the 2000s in Denmark, environmental measures and carbon emissions became salient concerns. In 2000, the Government published the first national energy action plan "*Energi 2000*", which included the long-term goal of reducing carbon emissions (DEA 2016a; H. B. Mortensen 2018). In 2012, the Danish Parliament signed another energy agreement, which stipulated that at least 35% of the energy supply should come from renewable sources by 2020 (DEA 2012). This Agreement is referred to as being a "wide" and "ambitious" accord (*Altinget.Dk* 2012; *Børsen.Dk* 2012).

This Agreement prescribed a rapid conversion of district heating from coal to biomass; a conversion which, according to the Minister of Climate and Energy of the time, Lykke Friis, would mean that district heating would *"play a very important role"* in the future of the Danish energy system (Lykke Friis in Völcker 2010, my translation). In 2012, the capital region also announced its ambition to become carbon neutral by 2025, thereby pressuring district heating actors to transform the heat production and distribution accordingly.

This section first explores how these ambitions led the regional DH actors to develop a series of new material devices: The *Heat Plan Copenhagen* (HPC) 1, 2, and 3. The section explores how these 3 plans can be considered inscriptive devices, and how they are used to steer the future development of the regional infrastructure. This is followed by a discussion of how pressure to transform the system (quickly) from coal to biomass came from different spheres and compelled the actors in achieving a defined 'energy transition'. Finally, the section examines how this coerced transition, together with the collapse of the framing of biomass as a carbon neutral resource, has led the DH actors to experiment with innovative district heating strategies.

5.3.1. AN "ALMOST CARBON FREE" GREATER COPENHAGEN DH

5.3.1.1 Copenhagen's first Heat Plan (HPC1)

CTR, VEKS, and HOFOR[11] organized the daily heat-load dispatch in the wake of the oil crisis, but they also wanted to find a way to coordinate the long-term planning of the DH infrastructure, presumably so that they could manage their investments. Therefore, from 2008 to 2009, the three actors collaborated and established the first 'Heat Plan Copenhagen' (HPC) (da. *Varmeplan Hovedstaden*). The aim of the plan was to assess future regional heat demand in order to be able to ensure regional security of supply at a low price for the customers, while taking into account national energy developments (CTR, Københavns Energi, and VEKS 2009). The plan assessed

[11] Under the name København Energi at that time, renamed HOFOR in 2013.

several scenarios regarding potential developments on the energy market, different levels of fluctuating energy resources integration, technological developments, etc.

A further aim of the HPC 1 was to "*create an interest for DH developments in Greater Copenhagen – as well as to convey companies' roles*" (Madsen 2008, 10). To this end, the three actors organized a launch seminar in June 2008 and invited a wide array of actors including business, universities, energy consultancy companies, the Danish Energy Agency, NGOs, district heat producers, building experts, as well as all the municipalities part of the transmission system. They also held private meetings to which only the municipalities and the municipal DH utilities were invited (CTR, Københavns Energi, and VEKS 2008).

HPC 1 is the first report of a series; two others have followed, and another is to be released in the summer of 2021. The HPCs circulate amongst the producers and regional DH utilities and contain projections of the future for regional DH infrastructure and guidelines regarding which infrastructural investments should be carried out in the region. For example, HPC 1 opens with the following:

> In the coming years, the various actors of the region will have to decide on a wide array of investments. (...) These investment decisions are to a large extent affected by the future framework conditions for the electricity and heating sectors. (...). There has therefore been a need to create an overview that can be used by the actors when decisions have to be made about the future heat supply in the metropolitan area. Hopefully, by analyzing different scenarios up to 2025, this report can contribute to the necessary overview and decision basis (CTR, Københavns Energi, and VEKS 2009, 5).

Therefore, the plans can be considered as coordination devices that influence decision-making processes. The HPCs help to reduce uncertainty by highlighting possible futures for the sector and the relevant actors– a future that is soon to become "carbon neutral".

5.3.1.2 Environmental concerns and carbon statistics

Climate change became a shared concern in Copenhagen and materialized in numerous municipal goals. For example, Copenhagen Municipality set the goals of becoming "*the world's first CO2-neutral capital*" (Copenhagen Municipality 2012, 4), soon followed by, among others, Høje-Taastrup, Albertslund and Roskilde, who planned to be carbon neutral by 2050, 2024 and 2035, respectively (Høje-Taastrup Kommune 2015; Albertslund Municipality 2015; Roskilde Kommune 2018). These goals increasingly prioritized carbon statistics calculations, which were, and are, presumed to represent the cities' sustainability (Rose and Miller 2008).

The transmission utilities, owned by the municipalities, were thereby pressured to phase out coal and achieve carbon reduction targets in time (CTR 2020). COP 15, which took place in Copenhagen in 2009, increased the pressure from the media and government on the DH actors. Morten Stobbe, currently vice-director at VEKS, recalls:

> Back in 2008, when COP 15 was to be held in Denmark, and the ambition of becoming CO2 neutral in Copenhagen by 2025 was formulated. (…) We started to work on [the Heat Plan Copenhagen] in 2008, and we presented it in early September 2009 because we wanted to ensure maximum media coverage before COP15, which was starting in early December. (Int. Stobbe, my translation)

Furthermore, since 1995, a regulatory measure intending to diversify energy resources had defined biomass as a carbon-neutral energy source, thereby exempting it from carbon taxation (DEA 2016a). This exemption generated "*a good business case to convert"* the CHP plants from coal to biomass (Int. Lillethorup, my translation) and, as the heat producers and utilities had to find a carbon-neutral solution quickly, biomass became attractive.

Therefore, stimulated by the economic mechanisms, subjected to political pressure and a (convenient) biomass framing, the producers and heat utilities were compelled to decree "*a fast transition to biomass*" (CTR, Københavns Energi, and VEKS 2009, 19). Henceforth, the transmission companies and heat producers discussed and decided which plants should be converted first, while continuing to ensure the security of supply.

Subsequently, Køge CHP plant was converted in 2012, Avedøreværket in 2016, and Amagerværket in 2020. Despite the high costs of the conversions[12], the process allowed the politicians and heat utilities to showcase significant carbon reductions – the carbon statistics showed a drastic transformation from energy being 77.7% based on fossil fuels in 2000 to being 68.1% carbon-free in 2019, as the following graphics Figure 7 illustrate:

[12] Estimated to be around 800-940 million Euros.

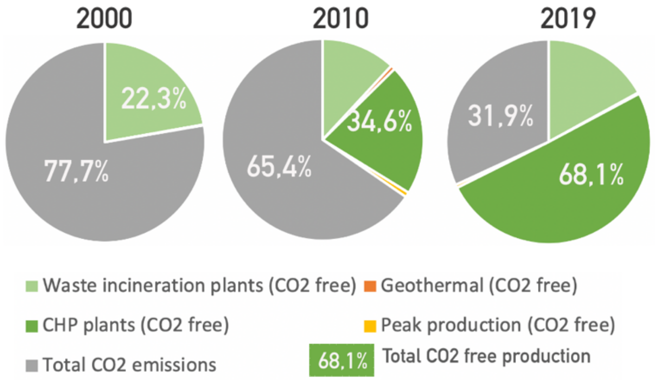

Figure 7: Evolution of the carbon statistics in Greater Copenhagen DH system from 2000 to 2019. Made by the author with data retrieved from CTR, HOFOR, and VEKS (2020).

As can be seen in Figure 7, in 2019, almost 32% of production still results in the emission of carbon. This comes from waste incineration plants, which emit carbon, the extent of which depends on how the waste has been sorted, as well as the use of peak load heat units, which are mainly based on oil. VEKS, CTR, and HOFOR have kept collaborating on a HPC 2, and 3, in order to continue to move towards a 100% carbon neutral DH system.

5.3.1.3 Heat Plan Copenhagen 2 and 3 and the collapse of the biomass framing

VEKS, CTR, and HOFOR continued to work on a low-carbon future for the Greater Copenhagen DH infrastructure. They realized the second HPC between 2010 and 2011, which included a roadmap of other "*priority measures for reaching CO2 neutrality by 2025*" (CTR, HOFOR, and VEKS 2011, 4). And, from 2012 to 2014, the actors worked on the third HPC, a report which opens with the following:

> Heat Plan Copenhagen 1 and 2 have primarily functioned as a dialogue platform between CTR, HOFOR and VEKS regarding the developments of the district heating system in the capital area. In HPC 3, the purpose has been to expand this dialogue platform and to also include the municipalities, the heat supply companies and the waste incineration companies. (CTR, HOFOR, and VEKS 2014, 5)

The HPCs are, thus, used for slightly different purposes; they are distinct inscriptive devices that enable particular actions. Nevertheless, their overreaching goal is to establish guidelines for future investments, and to include an increasing number of actors in order to achieve greater regional coordination.

Meanwhile in Denmark, the framing of biomass as a carbon-neutral energy source is gradually collapsing. Since 1995, the framing of biomass had been based on a simple understanding of the carbon cycle, which asserted that incinerated trees release as much carbon as they have consumed during their lifespan and are, therefore, carbon neutral. Nevertheless, a significant increase in biomass imports, growing concern about the potential future scarcity of the resource, and increased skepticism of the simplistic understanding of the carbon cycle, all contributed to a substantial controversy (From 2014; Bredsdorff 2018; *DR.Dk* 2020).

These concerns made their way into HPC 3, The plan questioned, for the first time, the role that biomass should play in the regional district heating system, and opens as follows: "*What will the role of biomass be for the district heating supply in the long-term? Is there enough sustainable biomass available? And how to balance considerations of sustainability, security of supply and economy?*" (CTR, HOFOR, and VEKS 2014, 6). Morten Stobbe relates:

> HPC 3 relates to a large extent to "What should the future after biomass be, what is the image we look at when we look into 2050, and how long can we run with biomass? What kind of technology is going to replace it?" (Int. Stobbe, my translation)

Even though the subsidies and tax system, along with political and media pressure, have compelled the actors to convert the power plants from coal to biomass, there is a gradual acknowledgment that the carbon neutrality of biomass is debatable (The Danish Council on Climate Change 2018). In 2018, biomass accounted for 64% of the categorized 'renewable energy sources' in Denmark; a figure which, it has been suggested, is out of proportion considering that it would require a forest roughly two times the size of Denmark to meet this consumption (Bredsdorff 2018). At the time of writing, critics from different political parties are becoming increasingly vocal in their criticism of the Climate Minister, Dan Jørgensen, who they consider has being too slow in proposing concrete plans for the phasing out of biomass (*DR.Dk* 2020).

5.3.2. EXPERIMENTING CARBON FREE FUTURES

As discussed above, HPC 3 is, to a great extent, concerned with the phasing out of biomass and, therefore, with finding alternative ways to produce and distribute heat. Producing the HPCs is consequently becoming increasingly complex, which is also reflected in the time it has taken to complete the plans; while HPC 1 and 2 took a year to publish, HPC 3 took two, and HPC 4 – to be published in the summer of 2021 – will have taken five.

HPC 3 concludes that the way to reduce biomass use is to transform the current regional heat provision towards "*a more decentral production structure with more heat producers*" (CTR, HOFOR, and VEKS 2014, 14). The report argues that decentralized heat production would permit the integration of solar heating, heat pumps, geothermal and surplus heat from industries. Nevertheless, the report points out that these "*new heating units will demand new requirements from the overall* *network and its operation*" (*ibid*.). Jonathan Thordal, an energy planner at Varmelast, explains why in the following:

> Varmelast wants to establish, as much as possible, an optimal heat and electricity distribution, and Varmelast is of course in the process of finding out how many small plants we need to integrate, and in what way. And a small company, like for example Roskilde DH Utility, which is relatively small compared to CTR and VEKS, may not have the taskforce and resources to send production files 6 times a day. (…) Also, we would need to know all the prices, also for the small heat pumps of 5MW and less, but the prices are very specific to the plants, to the electricity price forecasts, etc. (Int. Thordal, my translation)

Varmelast was built on the premise of dispatching heat from large-scale production units. Accordingly, changing its operation to integrate small, decentralized heat generation challenges its core foundation. As expressed by the energy planner's quote, their integration might require a reconfiguration of the "*economically optimal load distribution"*, as well as larger manpower capacities from the decentralized heat producers. Jonathan Thordal then adds that Varmelast, CTR, VEKS, and HOFOR have initiated a specific task force dedicated to addressing this integration issue.

Furthermore, the authors of HPC 3 also note that integrating these decentralized heat productions introduces another complication; decentralized production units can typically supply heat at about 60°C, whereas district heating grids are typically designed to supply heat at about 90°C. Therefore, the HPC 3 notes that "*[t]he development and testing of these [decentralized] alternative technologies must go hand in hand with lowering the network's temperatures"* (CTR, HOFOR, and VEKS 2014, 14). In other words, integrating decentralized production units must be combined with both a reorganization of Varmelast and a conversion of the distribution grids from traditional to low-temperature grids.

In light of these challenges, many experimental and pioneering projects have been initiated in the last years in Greater Copenhagen. For example, Høje-Taastrup Forsyning has developed an integrated strategy aimed at integrating local heat sources and lowering the temperature in the pipes. To this end, in 2018, the utility, among other initiatives, established an electric heat pump, which produces both district heating and cooling from which the excess heat can be stored and reused (Pedersen 2018), and an ATES (Aquifer Thermal Energy System), which provides heating and cooling. The innovative aspect of the project even prompted a visit by the then Climate Minister, Lars Chr. Lilleholt (Høje Taastrup Fjernvarme 2018).

Another pioneering project that is being conducted by the transmission companies and heat producers is the realization of the first regional Thermal Energy Storage (TES), which is projected to reduce the use of biomass by storing surplus heat and integrating fluctuating energy sources. The implementation of the TES is the subject of Chapter 6.

Furthermore, Albertslund Forsyning has also engaged in a DH strategy aimed at transforming its grid from a traditional DH distribution grid into a so-called "4th Generation DH", lowering the temperature from 90°C to 60°C, while integrating local heat sources. This transformation is the subject of Chapter 7.

Other experimental projects have investigated using buildings as thermal storages (Sandersen and Honoré 2018), developing heat communities (Copenhagen Municipality and Aalborg University 2018), establishing Carbon Capture Storage (Wittrup 2020), etc. These examples, despite not being an exhaustive list of all the ongoing projects, illustrate the gradual recognition of the need for decentralized production in Greater Copenhagen and the proactive efforts of the DH actors to become low carbon. These projects are resulting in new problems for Varmelast and the transmission utilities, as they challenged both short- and long-term planning and ways of thinking about the DH infrastructure. The administrative, contractual, and physical devices assisting the heat load dispatch in Greater Copenhagen may need to be redesigned in order to maintain an optimal heat load dispatch for the electricity and heat productions.

5.3.3. THE HPCS, DEVICES COORDINATING FUTURES

The overall goal of the three Heat Plan Copenhagen is to project a common DH future. They have a calculative dimension in the sense that they measure and make quantitative scenarios of the future; they calculate the extent to which certain technologies are to be promoted and others reduced. Furthermore, they also have an inscriptive dimension in the sense that they narrate a particular future with low-temperature grids and decentralized heat production.

In addition, the production of these plans represents an attempt by VEKS, CTR and HOFOR to integrate the regional DH actors and to establish a discussion platform for them. By circulating among the DH actors and mediating action, the HPCs represent a forum for deliberation about the future where different actors can voice their concerns. Consequently, the HPCs can be considered as being the results of "hybrid forums", i.e., the place where actors can contribute to problematizing and suggesting futures. They align problems, solutions, and interests. By conveying a particular version of the forthcoming developments, the plans make uncertainties manageable and facilitate the creation of a future of which the actors will be part. However, even though the three (and soon 4) HPCs are identifying issues, establishing courses of action, and reducing uncertainty, they all do so in different ways.

The first plan has mainly been used to mediate negotiations; it circulated amongst district heating utilities, energy analysts, experts, heat producers, and municipalities to establish roles. It was flexible enough to be understood in the different spheres in which it circulated. The HPC 1 conveyed the idea of long-term collaboration rather than it defined a precise socio-technical future to be constructed.

The second HPC was mainly a continuation of the first. Maintaining the status quo, it helped to strengthen the new collaboration and maintain "*a coordinated basis for decisions*" (CTR, HOFOR, and VEKS 2011, 4). However, as the actors became increasingly the subject of political and media pressure, tax/subsidy systems and environmental concerns, the heat utilities and heat producers were forced to convert the regional large-scale production units from coal to biomass. At that time, the actors' temporal room for maneuver was too short to explore alternatives to biomass. Nevertheless, these conversions hinged on a simple (and convenient) carbon cycle fact, which framed biomass as a carbon-neutral source of energy – a framing which is gradually collapsing.

Therefore, HPC 3 has been, to a great extent, the device problematizing the achievement of a future with a low use of biomass (Callon 1980). The plan helped the district heating practitioners to navigate the uncertainty related to the transformation to a low-carbon future, and established that the future would be low temperature, decentralized, and with a limited amount of biomass. As a result, DH utilities started to experiment with local solutions to the collective concern. Consequently, an increasing number of pioneering projects have appeared in the region, which has resulted in the emergence of new issues for Varmelast, whose premises may become obsolete in the near future.

To conclude, the three HPCs are material devices that coordinate a socio-technical future of which all the involved actors will be a part. The HPCs establish a frame of reference from which the involved actors derive a source of 'calculativeness' (Callon 1998) for their projects. The three HPCs have led to a gradual transformation of the initial ideas into being, reinforcing some of the established socio-technical elements of the network, while simultaneously helping to transform and bring others into being. Therefore, the inscription devices enable the actors to simultaneously preserve and transform their roles.

5.4. CONCLUSION

The Greater Copenhagen district heating socio-technical network has gradually become increasingly complex. Overtime, the infrastructure has become subject to social, economic, political, and organizational constraints. Stranded assets, geographical configurations, organizational divides, and regulations have limited the capacity for action and have produced compound problems.

The actions performed along the way have been supported by an array of devices which worked in specific ways. While some of them, as a result of their intertwinement, have ensured the continuation of a secure regional heat provision, others have enabled the projection of futures and the coordination of prospective actions. Altogether, these devices have helped to reduce uncertainties, coordinate futures, and stabilize worlds. Furthermore, the presence of social associations appears to have been extremely important for the operation of these devices. These social ties within the socio-technical network resulted in strengthened cohesion between the practitioners, thereby facilitating their cooperation. Physical devices (doors, locations, etc.) facilitated the establishment and durability of these relationships.

The analysis has also revealed that the Greater Copenhagen DH socio-technical network underwent the following three transitional phases: the oil crisis, the liberalization of the electricity system, and a current transition to a low-carbon future. These instances reveal that energy transitions are more discrete than generally assumed by transition scholars. In these instances, energy transitions are not a matter of S-curve technological evolutions (Kemp 1994; Geels 2002). Instead, they are the result of the practitioners' work in maintaining the security of supply despite the ongoing changes in their surroundings. Each instance eventually led to a particular form of energy transition, which transformed the district heating infrastructure and its social, economic, and organizational associations.

Moreover, by leaving the categorization of 'transition' open and by being attentive to the elements composing it, the analysis has revealed that the sustainability of the region is based upon the (convenient) framing of biomass as a carbon neutral energy resource, a framing which is today collapsing. The practitioners, caught by political pressures and a short timeframe, have been compelled to convert the regional heat production units despite their doubts upon its sustainability.

Concludingly, the analysis demonstrates that transitioning is not necessarily the result of orchestrated planning or a specific vision (Sovacool, Axsen, and Sorrell 2018), but rather of re-assembling situated socio-technical networks.

CHAPTER 6. COPING WITH UNCERTAINTIES: ESTABLISHING THE FIRST REGIONAL THERMAL ENERGY STORAGE

This chapter follows, with a "worm's eye" view, the five-year implementation process of the first regional pit Thermal Energy Storage (TES) in Greater Copenhagen. As mentioned in the previous chapter, the TES is one of the projects contributing to a transition of the district heating system towards a low-carbon future; it is one of the technologies that HPC 3 identified as being part of the targeted future with less biomass.

The technology in itself is not novel, and is not considered as a complex technology; it is "*a hole to dig in the ground with a plastic liner and an insulating lid*" (*Sn.Dk* 2019). The project has often been depicted in the professional media as an 'easy technology', and TES have been used in energy systems for decades. In general, TES are charged when the heat production costs are low and discharged when the heat demand is high. TES are, as such, a sort of thermal battery that buffers the heat demand and supply.

However, in this chapter, we will see that the implementation of the first TES in Greater Copenhagen was far from straightforward. Although the HPC 3 calculated and identified a need to multiply TES capacity by ten in the region, it did not establish how the technology should be operated or by whom. Therefore, questions related to its location, business models, and operation have remained unanswered.

The chapter is divided into three parts. The first follows the three sites where the idea of implementing a TES emerged and how, from a general idea, the TES became singularized, which transformed the conception of the technology that was to be implemented. The second part follows the difficulty the actors had in 'knowing' (or calculating, (Callon 1998)) the technology and how it should be operated, as well as establishing its business model. The final part analyzes some of the elements that allowed the involved actors, despite all the technological, organizational, and economic uncertainties, to find closure and implement the first regional TES in Greater Copenhagen.

6.1. THE EMERGENCE OF A “NEW” TECHNOLOGY

6.1.1. THREE SITES OF EMERGENCE

As introduced above, TES are not new technologies – TES have already been implemented in other regions of Denmark. For example, in 2012, a 75,000 m^3 TES was constructed in Marstal (a town of about 2,300 inhabitants located on the island of Æro) in connection with a solar farm (Aeroe-Emk 2020). Similarly, in 2013, a TES of nearly 70,000m^3 was established in the town of Dronninglund (3,500 inhabitants) in Northern Jutland, which was also in connection with a solar farm (Dronninglund Fjernvarme 2014). Or again, in 2014, a similar combination of solar energy and thermal storage was established in Vojens, a town of about 7,000 inhabitants in Southern Jutland (Wittrup 2014). All these TES are “seasonal storage”: the solar panels can charge the TES in the summertime when solar production is at its highest and heat demand is at its lowest, and return the heat to the DH grid in the wintertime when the heat demand is at its highest.

In Greater Copenhagen, two thermal storages have already been established; the two commercial CHP producers Ørsted and HEP have implemented “thermal accumulation tanks”, which are large insulated silos that can be filled with hot water at times of high electricity prices and low heat demand, at the power plants Avedøverværket and Amagerværket, respectively. The main difference between these two and the three TES discussed above is that the formers are external silos and are significantly smaller (ca. 20,000m^3) , whereas the latter are pit storage and are notably bigger (ca. 70.000 m^3) (CTR, HOFOR, and VEKS 2014).

HPC 3

In 2014, CTR, HOFOR and VEKS published HPC 3. The plan found that “*the optimal heat storage level (...) is up to ten times the current storage capacity in the heating system*” (CTR, HOFOR and VEKS 2014, 50). It was calculated that greater TES capacity would allow the further integration of fluctuating energy sources, specifically wind power. The HPC 3 states:

> [W]ind power will play a significant role in the electricity system in 2050, and, as such, there will be a greater need than today for plants that can produce flexibly when it is not windy (CTR, HOFOR, and VEKS 2014, 51).

The HPC 3 conveyed the idea of a regional future with high amounts of fluctuating energy and calculated that a higher TES capacity could allow CHP producers to capitalize from following the electricity market fluctuations. Using different scenarios and energy outlook (e.g, IEA Outlook, Dansk Energi), the HPC 3 showed that greater TES capacity could allow to reduce the use of peak load production, thereby leading to a decrease in heat prices. Establishing TES was also coherent with the plan to decrease the use of biomass through the further integration of decentralized low-temperature heat sources.

In other words, by making some of the properties of TES visible, HPC 3 framed it as a beneficial technology for the regional DH network. The inscription device made the technology an integral part of the DH future, just like wind power is part of the future – it inscribed it in the regional DH actors' frame of reference.

Although the report framed a higher TES capacity as being economically beneficial for both the DH producers and DH customers, this framing remained incomplete – many specifics of the technologies were not made visible. The report states:

> HPC 3 identifies a significant economic potential in investing in Thermal Energy Storages in Greater Copenhagen. The next step is to find suitable locations for establishing TES in relation to grid connection and space for the technical facilities, together with assessing when it would be best to establish TES over the forthcoming 20 years. (CTR, HOFOR, and VEKS 2014, 15)

Finding a location was described as being a constraint for two main reasons. Firstly, a TES takes up space and the availability and affordability of land plots in Greater Copenhagen is limited. Secondly, district heating pipes are so expensive that they can undermine an investment plan and, consequently, the location needed to be close to the transmission grid. Furthermore, the report also identified the need for further analyses of the operation of the technology – the HPC 3 did not assess the type of flexibility that the storage could bring, whether it would be seasonal like the projects in Marstal or Vojens, or if it would be short-term.

To sum-up, the HPC 3 brought TES into the shared regional DH projection of the future and has framed some of its benefits. However, the HPC 3 did not equip the actors to calculate the specifics of the technology, leaving its singularization open to further calculations.

Høje-Taastrup Forsyning (HTF)

Since 2008, the western municipality of Høje-Taastrup (one of the largest municipalities in Greater Copenhagen with approximately 35,000 inhabitants) had been working on reducing its municipal CO2 emissions. In 2015, the municipality established a Climate Plan Strategy with a new goal of becoming fossil-free by 2050; a strategy that identified district heating as one of the four main action points (Høje-Taastrup Kommune 2015). The municipal strategy stipulates:

> The efforts include an expansion of the district heating supply grid, increased utilization of local and renewable energy sources, the possibility of establishing a thermal heat storage, better utilization of surplus heat from industrial production, conversion to low-temperature operation in the

> district heating supply, and the provision of information on alternatives to oil-fired boilers to citizens and companies residing in areas outside the collective heat supply (Høje-Taastrup Kommune 2015, 7).

The municipal district heating utility, Høje-Taastrup Forsyning (HTF), which buys its heat from the transmission utility VEKS, started implementing the district heating strategy set out in the municipal plan.

By 2018, the strategy had resulted in the construction of 3,000 m2 of heat solar panels, a new energy center supplying both heating and cooling to a wholesale commercial market (Birnbaum 2019), another one based on groundwater cooling[13], and two heat pumps, one using groundwater and the other a local data center as a heat source (Kjemtrup 2019). HTF also offered its customers new services such as an incentivizing tariff system for optimizing heat consumption, as well as district heating on subscription (Høje Taastrup Fjernvarme 2020). Overall, the utility's strategy has been to use the local resources and to decrease as much as possible the temperature in the distribution grid. Uffe Schleiss, technical chef at HTF, relates:

> The idea of a Thermal Energy Storage came from the fact that we expected to have an incredible amount of local production. (…) in summertime, when the heat demand is actually the lowest. [With a TES], we could store the heat until winter. These were the first thoughts, because the existing heat storages in Denmark were seasonal storages. (Int. Schleiss, my translation)

The implementation of a TES would allow the utility to use its local production and it was, therefore, considered a cornerstone of the strategy. At this point, HTF did not calculate the size, investment and operation of the technology, but nonetheless started to search for a suitable location for its construction.

ARGO

At roughly the same time, the heat producer, ARGO, also started investigating the possibility of establishing a TES. ARGO is one of the three regional waste incineration companies and is located in nearby Roskilde Municipality. This municipality is also one of the largest in Greater Copenhagen and, consequently, it has a large heat demand. Waste incineration plants have a "waste duty", i.e., the duty to burn waste all year round. ARGO, like the two other incineration plants in Greater Copenhagen, produces roughly the same amount of heat around the year. However, the heat demand reduces drastically in the summertime and eventually becomes lower than the amount of waste the three waste incineration plants located in Greater Copenhagen are

[13] Called "ATES" and which was inaugurated by the Climate Minister, Lars Lilleholt, who welcomed the pioneering nature of the utility's projects (Høje Taastrup Fjernvarme 2018).

required to burn. Storing the heat seasonally from summer to winter would thus allow the incineration plant to improve its operation and business.

ARGO, inspired by the TESs built in Jutland, initiated a discussion with Roskilde Municipality which, at that time, was preparing a new municipal energy scenario (Bertelsen and Petersen 2017). The waste plant proposed the construction of a TES on municipal grounds; a proposition which the municipality agreed to. Roskilde municipality hence started to search for possible locations for the TES in 2015 and included the TES in the energy plan scenario (Roskilde Kommune 2015).

Three sites and three distinct reasons

To sum up, the idea of implementing a TES emerged at roughly the same time, at three different sites, and with three different concerns, as illustrated in Figure 8. HPC 3 calculated that the regional TES capacity should be multiplied by 10 to reduce peak load production and increase the integration of fluctuating energy resources, but remained unspecific about possible locations or about how a TES should operate. Both HTF and ARGO were considering using the TES seasonally; the former for integrating local and seasonal production in the municipal grid, and the latter for displacing the heat in the winter when consumption is high.

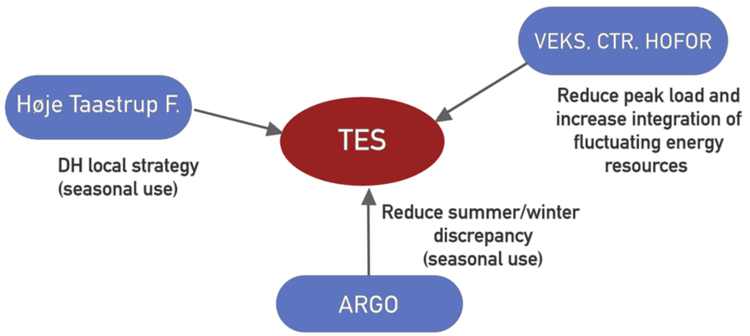

Figure 8: Illustration of the three sites for the emergence of the first TES in Greater Copenhagen

The TES was thus brought into being from three different sites, each of which had their own specific concerns. However, at this stage of the process, none of the sites had framed the technology entirely; the framings were combinations of local concerns and technological projections even though they did not delve into the specifics. Up this point, the TES was only an idea. The following section examines the practitioners' efforts to calculate and frame the technology.

6.1.2. SINGULARIZATION OF THE TECHNOLOGY

In 2012, ARGO initiated discussions with the consultancy company, Rambøll (involved in other TES projects in Jutland), to investigate the possibility of establishing a seasonal energy storage in ARGO's surroundings. In Bertelsen and Petersen (2017), Klaus W. Hansen, the vice-director of ARGO, says that the results of Rambøll's analyses concluded that the project was unviable:

> We made a project proposal which concluded that if the TES was to be run as an ARGO-storage, then the project would have a negative or close to 0 socio-economic benefit. But if it was established as a system storage, then there clearly was an economic profit to it. (Int Klausen in Bertelsen and Petersen 2017, my translation)

The analyses concluded that it would not be economically viable for ARGO to invest alone in a seasonal TES because of the significant investment and the unsufficient availability of surplus heat. On the other hand, it would be fruitful to implement the technology as a DH system component and to use it, not from one season to another, but daily or weekly. This had not been done before in Denmark. The municipality continued to identify possible locations for a TES – a project to which we return in section 6.3.2.2.

Høje-Taastrup Forsyning found a suitable location for a TES and bought it from the municipality, despite not having investigated the specifics of the technology further. Uffe Schleiss explains that they did so because *"[they] were sure it was going to be built*" and that "*the only question was about who was going to build it!"* (Int. Schleiss, my translation). This quote suggests that the projection in HPC 3 had translated the regional DH practitioners into a given future, where TES had an inherent role to play. The utility then engaged in dialog with VEKS, aware that the transmission company had an interest in increasing the thermal storage in Greater Copenhagen as indicated in the HPC 3.

VEKS and HTF subsequently started a collaboration and engaged two consultancy companies, Ea Energianalyse and Rambøll. Ea Energianalyse was hired to analyze the optimization of the TES, taking into consideration the regional DH grid, while Rambøll was hired to conduct the more technical analyses of the pipes, liners, heat exchangers, etc. In other words, VEKS and HTF associated themselves with new competencies for calculating the TES.

Jesper Werling, an energy consultant at Ea EnergyAnalyse, relates how they conducted "*a whole range of different analyses"* (Int. Werling, my translation), modeling different sizes of TES, different piping systems, different energy futures, different temporal operations (daily, weekly, monthly), etc. The analyzes calculated that the optimal size for the TES in HTF was 70.000m^3. The calculations, thereby, defined and transformed the technology from a general idea to a precise size and location (Ea Energianalyse 2017).

Furthermore, Jesper Werling relates that the analyses conducted by Ea EnergyAnalyse and Rambøll led to the increasing realization that establishing a thermal storage could not be done for the sake of only one actor but instead had to be implemented as a piece of regional infrastructure. Jesper Werling relates:

> It was an acknowledgment process, because the investment alone is so expensive that it would not be economically feasible only to store heat from summer to winter. To make the investment profitable, it is necessary to use it together in the system. (Int. Werling, my translation)

The calculations made by Ea EnergyAnalyse and Rambøll brought another TES into being than the one originally considered; the TES became singularized from the general idea of establishing a stand-alone energy storage to being a shared piece of infrastructure. This subsequently meant that all the heat producers and utilities that were part of the regional DH grid were ought to be involved in the project.

The analyses also confirmed that the TES could not, or only to a small extent, enable seasonal heat storage, although this was the premise for building the TES for both ARGO and HTF. Jesper Werling explains that "*The more the TES is used, the more benefits it will bring",* and that "*If the TES is tied only to store solar heat or incineration heat, the investment will not pay off at all"* (Ea Energianalyse 2017, 6, my translation). In other words, calculating the TES transformed and brought into being a different TES than the one that had been originally conceived; it was requalified as a an infrastructural improvement that had to be operated as a short-term storage. Furthermore, at that time, only seasonal heat storages had been built in Denmark. The calculations thus re-framed the TES from being a 'known' technology into being an 'experimental' technology. This enabled VEKS to receive a EUDP grant to support the newly qualified "*pioneering project*" (Email correspondence with T. Hartmann).

Roskilde's DH utility and ARGO continued investigating locations for the construction of another TES, assured by the HPC 3 that the TES capacity would continue to increase in the coming years. Furthermore, the experimental character of the TES in HTF may have persuaded ARGO to 'wait and see' how the first project would transpire and learn from it, before engaging in a similar project.

6.1.3. FROM "LONG-TERM AND INDIVIDUAL", TO "SHORT-TERM AND COMMON" TES

In Greater Copenhagen, the idea of implementing a TES emerged from three different sites with respective concerns that needed to be addressed, namely HPC 3 for integrating more renewables, ARGO for solving the winter/summer discrepancy, and

HTF for integrating local heat sources. All three had different reasons for using a TES, but all three referred to existing TES projects in Jutland. The idea of implementing a TES thus resulted from the combination of a general technology and a particular (or 'situated') concern. In other words, the three sites had different problems but a shared identified solution. At this early stage, the framing of the TES remained incomplete; the only information that was stabilized were the benefits that TES made possible in other locations.

The technology that was at first considered 'easy' ("*a hole to dig in the ground*", (*Sn.Dk* 2019)) by the practitioners in Greater Copenhagen turned out to be more complicated. Its technological and economic properties were yet to be defined and stabilized in Greater Copenhagen. The TES had to be displaced from a general idea to a specific location with a specific socio-technical network.

As VEKS, ARGO and HTF did not have the capacity to calculate the technology with their own equipment (or 'material devices'), they entangled themselves with new competencies and hired Ea EnergiAnalyse and Rambøll. These two companies calculated the TES and displaced it from a general idea to a singular technology in Greater Copenhagen district heating (socio-technical) network. From being an outside projection, the TES became an element part of the socio-technical network. And alongside this displacement, the TES was transformed. From being a "seasonal and individual thermal storage", the TES became a "short-term and common thermal storage of 70.000m^3 located in HTF". The technology was requalified as a piece of the Greater Copenhagen district heating infrastructure.

This requalification meant that the technology had to be operated in a radically different way as originally projected, which provoked new economic and organizational considerations. From this point forward, it was not only HTF and VEKS that were involved in the project: all the heat producers also had to be involved, which prompted the need for further calculations.

6.2. ESTABLISHING A BUSINESS MODEL

The process of calculating led to the conclusion that the first TES should be built on Høje-Taastrup Municipality's ground, should be 70.000m^3, and that it was to be implemented as a piece of the regional district heating infrastructure. This new framing of the technology raised a whole array of new questions, of which a crucial one for the practitioners concerned its economic model. Who was going to pay for the infrastructural improvement, and what business model should be established?

Ea EnergiAnalyse estimated an approximate yearly benefit of 5-7 million kroner (670,000-950,000€/year) for the entire district heating system, but of the five heat producers and two DH transmission companies, who would actually receive these economic benefits?

This central question could not be answered without first answering others: how should the storage be operated? By whom, and with which access rights? And how much would the heat cost? And also, to which grid should the TES be discharged? In other words, the framing of the technology as being an infrastructural improvement raised new concerns and problems, which introduced new uncertainties that had to be framed.

The following sub-section discusses the main concerns that arose and the actors' efforts to complete the technology's framing. The first part follows the concerns related to the investment costs, and the second follows the manifold issues related to how to operate and run the TES.

6.2.1. FINANCIAL CONCERNS

Ea EnergiAnalyse estimated that the establishment of the TES would result in a yearly benefit of about 5-7 mio. DKK for the Greater Copenhagen district heating system. Based on general assumptions about heat price agreements between the producers and the transmission companies, the consultancy company estimated that, out of the yearly benefits:

- the CHP producers (Ørsted and HEP) would get 30-35%,
- the waste incineration (ARGO, ARC, and Vestforbrænding) would get 10-30%,
- and the heat customers would get between 35-60% (Ea Energianalyse 2017, 8).

According to VEKS and HTF, these calculations entailed that the waste and CHP producers would also have to participate in financing the project as they would also receive an economic benefit from it. In Bertelsen and Petersen (2017), Jens B. Sørensen, a project developer at VEKS, explains that the transmission company engaged in a negotiation and demonstration process with the heat producers:

> The storage will be a part of the infrastructure, which means that all stakeholders must pay for it. And they should, as much as possible, get their return on investment. (...) So we have to do some calculations in which all the stakeholders have to believe. (Int. Jens B. Sørensen in Bertelsen and Petersen 2017)

However, what was known of the technology up to this point did not allow Ea EnergiAnalyse to make more accurate calculations than those mentioned above. As a result, the estimation range provided by Ea EnergiAnalyse remained quite large, between 5 to 20% difference. Furthermore, because the cost of the infrastructure was estimated to be around 70m DKK, this range made a significant difference for the producers. And moreover, the calculations made by the consultancy company were based on their assumptions of undisclosed contractual heat prices, so the margin of error was difficult to assess for the heat producers and heat utilities.

To compare and challenge the results provided by Ea EnergiAnalyse, the 5 different heat producers mobilized their own calculative devices to make their assessment of the technology. For example, Bjarne Lillethorup, contract manager at Ørsted, relates:

> VEKS had made some calculations that showed the operational economy of the TES. And it showed a significant economic benefit for Avedøverværket [one of Ørsted CHP plants]. Then we made our own calculations. We have (our own) simulation program. (Int. Lillethorup, my translation)

Also, in addition to having different simulation programs, Bjarne Lillethorup also remarked that the heat producers had different information to Ea EnergiAnalyse; the producers knew exactly how much of the storage their respective plants could use and when. However, they also had to estimate how much of the storage the other producers' plants could use to calculate their own benefits. Ea EnergiAnalyse and the five heat producers had access to different information and were using different devices to calculate the situation. Consequently, the practitioners' calculations of the TES differed.

Furthermore, calculating the technology's economic benefits also depended on the ownership of and rights for using the TES, which, at that time, had not been negotiated. And defining the technology ownership was complex since it entailed that the heat producers, who were competing on the same electricity market, could eventually own and/or use a common technology to out-compete each other.

Therefore, at the time, it was suggested that only the DH companies would own the TES, and the CHP producers would pay a rent or a tariff for having the right to use the storage. Bjarne Lillethorup, contract manager at Ørsted, relates that this was unusual in the sector:

> It is difficult for Ørsted to finance something that we are not owning, even though it can prove to be a positive business. There are many people who do not understand that we can make money without owning something. (Int Lillethorup, my translation)

If the district heating utilities owned the TES, then the energy producers would have to pay the DH companies, which would transform their trade configuration. Thomas Hartmann, energy planner at VEKS, relates:

> They [the producers] think that it is quite easy when we are the ones buying heat from them. But when the roles are exchanged and that, all over sudden, they are the ones in need to buy storage capacity from us, then it

> is not that east fir them anymore. They are not used to buy services from us. That is one of the challenges that there is in this project. (Int. Hartmann by Bertelsen and Petersen, my translation)

This suggests that this form of ownership was unusual and that the CHP producers would have found it difficult to accept as it could have transformed the traditional distribution of agency between the buyers and sellers.

In addition, the producers were also challenged by the uncertainties related to future fuel prices, heat demand, and other DH infrastructural changes when estimating their respective benefits. Bjarne Lillethorup explains that "*it is very difficult to calculate these things*", and relates an additional aspect further complicating the matter:

> In Ørsted we have, in general, higher business requirements that the DH companies. So, in that sense we are a little bit challenged in this project, because if they get 4% profits, they are happy, but our requirements are higher. We compete in principle with wind power parks, and there the returns on investment are higher than 4%. (Int Lillethorup, my translation)

The district heating utilities and the waste incineration plants are non-profit, whereas the commercial heat producers (Ørsted and HEP) have different business model requirements. As such, the empirical materials suggest that the involved actors had different expectations regarding the returns on investment, which had an impact on their understanding of how the bill should be split. Thomas Hartmann, energy planner at VEKS, relates in the following that the transmission company did not foresee that the establishment of a business model for the TES would be so challenging:

> We were hoping that we could make a simple calculation method where the producers would pay according to their heat production, a bit independently of what the calculations said that they would get. (...) A simple model, but none of them wanted to go with it. They all said, "no no, we will only pay according to the benefits we will get". And then they said "and what are the guarantee for getting these expected profits?'. (Int. Hartmann by Bertelsen and Petersen, my translation)

If the involved actors acknowledged that the TES would generate a profit for the entire DH system, themselves included, there was a multitude of elements that made it difficult for them to calculate and make their own benefits knowable. The respective profit uncertainties, the discomfort of co-owning or co-investing in a non-exclusive technology, the change in agency between buyers and sellers, the uncertainties related to the future developments of the energy system, all engendered different concerns for the actors, which rendered the financing process eminently complex. The lack of stabilized information hindered the actors' calculations and left room for too much uncertainty, which, as a result, hampered the actors' capacity for action.

The business model can be considered as a calculative device, which, more than revealing the world precisely, is a device operating as a mediator amongst the 5 producers, the heat utilities, and the energy consultancy. The business model appears to be a circulating device that all actors need to agree upon in order to go further with the process.

6.2.2. TECHNICAL CONCERNS

This section follows the technical uncertainties that emerged during the framing of the TES. One of the main technical concerns was to define the pipe connection between the TES and the regional DH infrastructure. The calculations of Ea EnergiAnalyses had established that the storage was to be 70.000m^3 and that it should be charged from the transmission grid (to which all the producers supply their heat) to benefit the regional system. However, the calculations did not establish whether the TES should be discharged to Høje-Taastrup Forsyning's distribution grid, or back in the transmission grid. Both solutions had their advantages and drawbacks.

HTF's distribution grid supplies approximately 35,000 customers, which limits its ability to discharge the 70.000m^3 entirely. This could reduce the TES operation, constrain its use and weaken its business model. On the other hand, HTF's distribution grid had the advantage of being at the same temperature as the water stored in the TES, that is, approximately 90°C. Therefore, there would have been no need to adjust the temperature of the heat stored in the TES to the temperature of HTF's distribution grid.

In contrast, the transmission grid supplies more than 500,000 customers and would consequently have sufficient capacity to discharge the TES entirely. On the other hand, the temperature of the transmission grid is approximately 110-120°C, which meant that "*one couldn't place [the TES] in the transmission network without doing something extra*" (Int. Werling, my translation). Adding a heat pump would have allowed an increase in the temperature and enabled access to the transmission grid, but it would also have required investing in a Power-to-Heat technology. This would imply at least two things: first, it would increase the investment costs, and second, it would entail relying on low electricity prices for using the heat pump and discharging the storage. In addition to these concerns, the use of a heat pump was also linked to a debate about the current and future tax/subsidy imposed on the DH sector. At that time, heat pumps were subject to high taxes for converting electricity to heat, which drastically limited their business case, but a debate and political discourse were suggesting to modify these taxes in the near future (Øyen 2018).

As neither of these two discharging solutions was satisfactory for the heat producers, Ea EnergiAnalyse proposed a third solution, namely, discharging the TES to the return pipes of the transmission system. In this way, they could avoid adding a heat pump and it would grant access to large discharge capacity. However, this solution would have increased the return temperature of the transmission system. Niels Henriksen, an analyst at HOFOR, relates:

> If the TES was to be discharged in the transmission's grid, it would have been in the return pipes, and that seems absurd. I mean, taking heat directly from the supply delivery, to the TES and to put it back in the return transmission pipes, it's … I mean! I think it is a little absurd! (Int. Henriksen, in Bertelsen and Petersen 2017, my translation)

This quote suggests that the third considered option was not welcomed by the heat producers as it did not appear logical, and that this solution was counter to a new engineering discourse claiming the efficiency of low-return temperature DH grids.

Another concern raised by both Ea EnergiAnalyse and Rambøll was related to how the materials of the TES would react to the short-term operation of the storage. Using the storage, not from one season to the next, but every week, would have meant that the temperature on the top of the storage would have been higher than in a seasonal storage. Jesper Werling explains:

> The storage needs to be emptied and filled up 30 times per year, so it will be to a much higher extent hot on the top. And that means that the plastic liner covering the storage must tolerate much higher temperatures, and we are a little bit worried about the technical lifetime. (Int. Werling, my translation)

As operating a TES in this way had never previously been done, the practitioners had no guarantee that a 'regular' insulation liner would hold and would be able to tolerate the higher temperature. This concern compelled the actors to investigate further whether or not it was possible to operate the TES as such.

Other uncertainties were also related to the future of the Greater Copenhagen heat load dispatch. As mentioned in Chapter 5, the introduction of decentralized heat production units (such as the TES) challenges the daily operation of Varmelast; Varmelast was built on the premise of dispatching centrally produced heat to decentralized heat consumers. The heat producers and the heat utilities were, therefore, concerned about Varmelast's future organization. According to the analyses made by Ea EnergiAnalyse, the TES had to be completely charged and discharged at least 26 times per year for it to be economically beneficial. Whether or not Varmelast would be able to ensure that this operation could occur (and what spillovers it might entail for other decentralized technologies) appeared to be difficult to assess for the producers and heat utilities. In other words, the lack of stabilized information concerning the future of the regional DH system was making it difficult to know and frame the TES.

Furthermore, Jonathan S. Thordal, an engineer at Varmelast, adds that "*there are several hydraulic constraints along the way, making bottlenecks and affecting how much we can utilize [the TES]*" (Int. Thordal, my translation). In other words, using the TES was also constrained by the physical layout of the regional DH pipe system. And besides, Jens B. Sørensen, a project developer at VEKS, relates that it would not have been possible to measure exactly how much heat the five producers would have been able to store precisely and when. He explains:

> It could be that there was on the TES five metering devices [one for each producer] measuring where the heat being stored would precisely coming from, but that is not how the reality is. There is no documentation that can afterwards say which producer has stored how much heat. And the amount being stored is so little in comparison to how much they produce that they cannot calculate it from their side either. (Int. Sørensen by Bertelsen and Petersen, my translation).

Even monitoring devices would not have enabled the heat producers and heat utility to measure precisely how much the five producers would use the TES and when. This, in turn, complicated the matter of assessing the respective earnings even more.

It seems that the more the actors tried to know and calculate the technology, the more technical properties of the TES had to be settled, and, consequently, the more concerns arose. Framing the technology called for several attempts to calculate its qualities and properties, which, intertwined with economic and organizational matters, was generating overflows.

6.2.3. SUMMARY

This section has discussed the concerns and issues that appeared during the framing process of the TES. During this stage (2017-2019), the involved actors were uncertain about the ownership model, the business model, and the technicalities.

The analyses conducted by Ea EnergiAnalyse qualified the technology's size and short-term operation and also provided a rough estimation of the involved actors' annual benefits.

These calculations were the starting point for VEKS and HTF to build a business model. The business model was used as a circulating device, equipping VEKS and HTF to enroll the five producers in the technology implementation process. The calculative device mediated the negotiations with the producers and was, therefore, a central element on which VEKS and HTF relied.

The business model was, however, only partially successful in enrolling the heat producers; whereas they may have been convinced about the possibility of earning profits from the TES, they remained doubtful about the extent of these individual profits. Consequently, they mobilized their own calculative agencies to calculate and know the technology. However, as each of them had access to different information (e.g., their marginal costs) and different calculative tools (e.g., different modeling software), they all calculated the TES and the profits differently and arrived at different conclusions. Besides, each of the heat producers had their own interpretation of what a good business model was. In other words, due to their situated (socio-technical) network, the five energy producers had different calculative agencies for knowing and framing the TES.

It can be argued that there was symmetry in the heterogeneity of calculative agencies; all the involved actors lacked stabilized information and equipment to fully know the technology. They were symmetrical in their inability to fully calculate the TES and as such, none of the actors dominated the others in the negotiation process.

At this point in the process, the business model, therefore, appeared to be a barrier to the implementation of TES. The process appeared to be at a "dead-end" as it was not possible to calculate and frame the technology's benefits further, thereby leaving the district heating practitioners in a situation of uncertainty. Furthermore, the empirical materials show that the involved actors could not establish and negotiate a common business model as long as the technical properties of the technology were not fully known or framed. However, these properties were highly dependent on the socio-technical network in which the TES was to exist; a network which was itself in the making and, therefore, uncertain.

This created a wicked situation: the business model could not be established as long as the technology was not fully known and *vice versa*. Consequently, the actors were caught in a paradoxical position in that they needed to take a decision (and thus calculate) but did not have access to stable information about the technology itself. Furthermore, the process of knowing the technology took place against a backdrop of uncertainty, where the lack of stabilized information appeared to result in deadlock between the actors.

Nevertheless, despite all the aforementioned intertwined issues, the practitioners did come to an agreement. The following section examines how the multiple involved actors found closure and established the first short-term TES in Greater Copenhagen.

6.3. FINDING CLOSURE

This last section focuses on two developments. First, it explores how an agreement to finance the TES was reached, and second, it explores the effects of the TES on Høje-Taastrup Forsyning's strategy, as well as the technological future of Greater Copenhagen.

6.3.1. CLOSING THE DEAL

Finally, in 2019 (around five years after the initial TES idea emerged in Greater Copenhagen), VEKS, Høje-Taastrup Forsyning, and the five heat producers came to an agreement. The business model, despite having been in the middle of the involved actors' negotiation process, was gradually cast aside. It was decided that HTF and VEKS would both own and invest 50% of the TES to avoid co-ownership of concurrent energy producers and that the 5 producers would pay a fixed annual payment over the next 20 years. Also, maintenance and transaction costs will be paid regularly according to the expected utilization of the heat storage. It was also decided to discharge the TES in HTF's grid and to establish the storage with a double and thicker liner to resist the high temperatures (Bernth 2020). Figure 9 illustrates how the TES will be connected to the regional and municipal DH grids:

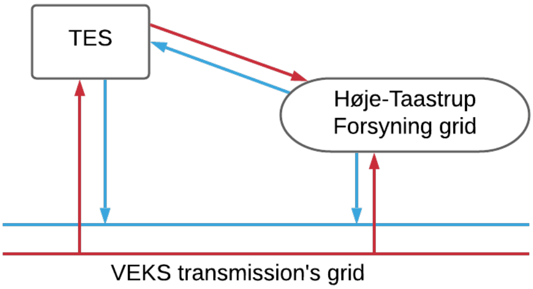

Figure 9: Illustration of the TES connection to the grid, made by the author and inspired from VEKS and Høje Taastrup Fjernvarme (2017, 3)

Despite the heterogeneity of calculative agencies and the lack of available information, the first short-term TES should be operational in Greater Copenhagen by 2021. The following sections explore how the actors managed to make the technology actionable.

6.3.1.1 Importance of social relationships

Thomas Hartmann, an energy planner at VEKS, recounts that agreeing about the TES involved *"many small complications"*, and continues:

> It makes us want to stop, but it has certainly not stopped. I actually think that there is a good atmosphere around it and good resources. But it is enormously demanding. Two transmission companies, three waste incineration plants and two commercial heat producers which all have to be guided in the same direction, it is demanding! (Int. Hartmann, by Bertelsen and Petersen, my translation)

The energy planner talks about the complexity resulting from the multiple actors involved. Nevertheless, he notes that there is a "good mood" shared by the practitioners. He, for example, explains that VEKS accepted a lower share of the benefits because what mattered to them was the successful implementation of the technology, more than receiving the exact profits. He relates:

> Different calculations have shown some different percentages [of received benefits], but we could agree to 56% instead of 53% to show some goodwill, also because this is a demonstration project. (...) For us, [the benefits] just have to be positive. (Int. Hartmann, my translation)

Thomas Hartmann explains that calculating slightly different operations of the TES led to slightly different conclusions regarding the benefits. However, the project proposal only had to demonstrate reducing the regional heat prices and carbon emissions to be feasible.

Bjarne Lillethorup, employed at Ørsted, similarly relates that the TES is "*a sign that the collaboration works*" because "*It is a faith process to make such an agreement, and it has succeeded."* (Int. Lillethorup, my translation). These three quotes point to the importance of the inter-organizational relationships for the successful implementation of the TES. It appears that the social ties examined in the former chapter section 5.2.2 played a significant role in the implementation of the TES. The regular formal and informal meetings, the commitment to the infrastructure, the trust stemming from and through the socio-technical networks appear to have facilitated the implementation of the TES.

Furthermore, the actors decided to establish a "*follow-up group where all the involved stakeholders will hear about how the TES operation is going*", relates Jesper Werling from Ea EnergiAnalyse (Int. Werling, my translation). The five energy producers and the heat utilities have agreed to meet regularly over the two years following the implementation of the TES to fix any potential discrepancies between the theoretical and the actual business model and operation of the storage. The "follow-up group" may also have made participating in financing the technology more acceptable to the producers as it ensured that the possible discrepancies could be adjusted at a later point in time.

Furthermore, Uffe Schleiss adds that the heat producers' willingness to be part of the project may also have been related to the relatively small investment required compared to the certainty of making a profit. He relates:

> It turns out that there is a lot of money to be made for them [the heat producers], and what is also important is that the investments they had to make were not very high compared to the investments they typically make. I don't know if that is what made it easier for them to be part of the project, but I at least think that it has been a part of it. (Int. Schleiss, my translation)

This suggests that the heat producers' willingness to invest in the TES may also have been connected to their ranking of risks. Heat producers are used to dealing with large long-term investments where uncertainty is significant, which always limits the accuracy of the results. Therefore, being used to dealing with a form of uncertainty together with the certitude of generating profits (both collectively and individually), combined with the relatively small size of the investments, may all have been elements that increased the heat producers' willingness to be a part of the financing.

6.3.1.2 Being part of a common future

As mentioned above, HPC 3 identified the need to multiply the regional TES capacity by ten, which meant that not only one TES was needed, but many. Uffe Schleiss, from Høje-Taastrup Forsyning, relates:

> ARGO and Roskilde district heating utility are also in a TES implementation process, and there are many others that want to establish storages because the HPC says '*This is the future. If we are to produce heat cheaply, then this is the way to go'*. I just think that people have been able to understand the direction pointed by the HPC. (…) This [TES] is a "first mover" about how the next one is to be established. Because there is no doubt about that, we need more, and most probably some that will be even bigger. (Int. Schleiss, my translation)

It thus appears that there was an acknowledgment that this TES was going to be only the first one of a series. As Jesper Werling puts it, "*HPCs are like the framework for the future investments*" (Int. Werling, my translation); the HPC 3 calculative-narrative device had defined and established a common future for the DH actors, a future with more heat storages. Therefore, refusing to take part in the first TES investment would be similar to refusing to be part of this common future.

6.3.2. TES IN HTF AND GREATER COPENHAGEN

The establishment of the TES in HTF however turned out to have different implications than expected for the municipal DH utility. The next section delves into the paradoxical situation in which the utility finds itself today, while the subsequent section returns to ARGO's project of implementing a TES close to their incineration plant.

6.3.2.1 From expectations to reality: HTF and the TES

Initially, HTF wanted to construct a thermal energy storage on their ground so they could integrate as much local surplus heat production into their district heating grid. This goal was, however, undermined in the implementation process. Uffe Schleiss explains that they actually "*cannot use the heat storage for [their] own heat production",* and that the TES even challenges its integration. He explains:

> The agreement [with VEKS and the producers] is based on the fact that we must discharge the heat storage. And, consequently, our local productions are not prioritized. (…) All the heat pumps that we have installed must be stopped if the TES is to be discharged. (Int. Schleiss, my translation)

HTF is now in this paradoxical situation where, although their interest was to increase the use of the local heat production, they are now limited by the TES. It is VEKS's control room that will decide whether to give discharge priority to the TES, and, therefore, whether and when HTF will have the right to use their local production. Installing the TES has ended up limiting the local strategy of the utility, who must now find "*a middle ground*", where both the TES and the local heat production can be used. Uffe Schleiss remains confident that, although "*it will not be very easy*", it should still be possible (Int. Schleiss, my translation).

Despite having been the initiator of the project, the utility has been caught in the making of the technology. The utility could not have known at the beginning of the project that what they had claimed was a solution for integrating local heat production would eventually become a limitation to it, at least to some extent.

6.3.2.2 TES Outlook

In March 2020, the waste incineration companies ARGO and Vestforbrænding together with Ørsted, HOFOR, VEKS, CTR, Roskilde Municipality, and Roskilde DH utility announced the establishment of a second regional short-term TES. In a communication to the journal Energy-Supply, VEKS states:

> We do not know the exact size of the future heat storage in Roskilde yet - the preliminary investigations have not yet begun. The possible future heat storage in Roskilde will, to a large extent, be based on our experiences from Høje Taastrup. (VEKS in Pedersen 2020, my translation)

At the time of writing, the first TES is being built in Høje-Taastrup, and Roskilde's municipality and VEKS have identified a location for the second. In the latter, Ea EnergiAnalyse has again been hired to carry out the system analyzes and Rambøll to look into the details of the TES connection (K. Hansen 2020). The heat utilities and the consultancy companies can now build upon their experiences from the first storage to implement the second.

6.3.3. A TECHNOLOGY EMERGENT BY DESIGN

Despite the complexity of the project, at some point (some time in 2018), the business model was pushed into the background of the technology establishment process. The investments have been made despite the lack of an accurate and finite business model. From being the predominant contentious point, the accuracy of the value creation has been pushed to the back and seems to have become a side issue.

The materials suggest that there are several reasons for this. First, it appears that the pre-existing social ties were of major importance for facilitating the economic negotiations. The producers and heat utilities know one another and have had past collaborations. The practitioners seem, therefore, inclined to show 'good will' to one another.

Second, although they could not calculate it accurately, the actors were certain to get some benefits from the TES. Furthermore, a "follow-up group" assured them that discrepancies between the established business model and the technical operation of the technology would be addressed, thereby reducing the investment risks. This follow-up group mirrors the actors' commitment to equitably redistribute the benefits from the infrastructural improvement, thereby helping to reinforce trust between the practitioners.

Third, the HPC 3 had already enrolled the producers and the district heating utilities in a shared prediction of the future in which the TES had to exist. Therefore, neither the business models nor the technical scenarios had to build a world of their own, for the world in which the TES was to be implemented already existed. The TES was thus a technology that was already part of the envisioned future, a future that the producers and the heat utilities want to be a part of. If a heat producer had declined the opportunity to take part in the TES investment, it would have signified their disapproval of being part of this collective future.

To synthesize, the successful establishment of the TES is an effect of the socio-technical network configuration. The gradual stabilization of the technical, economic and organizational characteristics of the TES enabled the practitioners to implement the technology and to accept a certain degree of uncertainty. The trust between the involved actors and the stability of the future represent the backdrop against which the calculations and actions are unfolding.

However, the making of the first regional TES has entailed unexpected consequences for HTF. The utility has found itself in a situation where the technology has undermined the premises upon which the idea originally emerged. Ironically, the TES hinders the integration of the local heat production instead of facilitating it. This illustrates that processes are always in the making and emergent by design (Garud, Jain, and Tuertscher 2008) and can, consequently, never be entirely predicted.

6.4. CONCLUSION

This chapter has followed the 6-year implementation project of the first Thermal Energy Storage in Greater Copenhagen District Heating socio-technical network. It has shown that energy transitions are not straightforward matters of technological management from a "protected space" to a "regime" (Geels 2002; Roberts and Geels 2019). Instead, it is a work of displacing and making known (and thus, actionable) a technology in a situated socio-technical network. In this case, the displacement of the TES in Greater Copenhagen transformed it from being an ‘individual and long-term storage’, to being a ‘piece of infrastructure and short-term storage’.

Furthermore, whereas the TES was expected to facilitate HTF local heat production, it is instead hindering it. The unexpected turns of events shows that the process of establishing a technology can never be predefined and is rather always *in the making*. Although Garud, Jain and Tuertscher (2008) study the design of two organizations (namely Linus and Wikipedia), their notion of ‘incompleteness by design’ captures what happened in the establishment process of the TES. The scholars posit that “*A scientific approach to design — one that requires complete representation of the problem and identifies the optimal solution — is based on the assumption that the environment is stable*.” (354). By analogy, the evolutionary economic approach assumes that the world is stable and that, once the ‘radical technology’ optimal design is discovered, it can break through the regime (Kemp 1994; Geels 2002; Carlsson and Stankiewicz 1991). The implementation process of the TES has rather shown that the technology is continuously being re-designed and re-framed by the actors, and that it is never complete. The follow-up group and the further evolution of the heat (socio-technical) network will keep redesigning the technology. In other words, energy transitions cannot be neatly prepared in advance and then evolve linearly like an unfolding mat; rather, energy transitions do not pre-exist themselves and are ‘emergent by design’.

This chapter has also shown that diverse material devices are assisting the district heating actors in coping with uncertainty in their work of preparing a low-carbon future. HPC 3 has calculated and narrated a particular future, Ea EnergiAnalyse's analyses have singularized the TES and have brought its technical specificities into existence, and the business model has circulated amongst the practitioners. Furthermore, this chapter has demonstrated that the success of a business model is not resulting from its accuracy in representing the world, as assumed by business model innovation scholars (Richter 2012; Helms 2016). Rather, as in Doganova and Eyquem-Renault (2009), this chapter finds that business models are circulating devices which allow coordination between practitioners, and which enable a certain degree of information stabilization. However, specifically in this case, the business model is not “*a mix of story-telling and calculation*” (*ibid*., 1562). Instead, it appears that the narration, which gives coherence to the business model’s calculations, is derived from another device, namely, the HPC3. Therefore, this analysis contributes to the reflection proposed by Doganova and Eyquem-Renault (2009), as it suggests that in different ventures, business models may be more or less distributed.

This chapter has also revealed that technology implementation processes are not necessarily the result of straightforward economic applications (Kemp, Schot, and Hoogma 1998; Bergek et al. 2008). By revealing the details of the work required to make the TES knowable and actionable, this case has revealed how the interconnected social ties, concerns, and goals co-evolve in energy transition processes. In this light, the uncertainties and the presence of social relationships are not a subsequent dimension of technical implementation, but rather integral parts of the socio-technical network.

Also, in this case, it seems clear that, for the practitioners, energy transitions are a matter of making their future financially viable through the preparation of business models and calculations. Çalişkan and Callon (2010) refer to this process as 'economization', that is, "*the processes through which behaviours, organizations, institutions and, more generally, objects are constituted as being 'economic'*" (2). This inquiry has revealed the work of the practitioners in analyzing, describing and making the TES actionable as a part of the energy transition, and, simultaneously, in making themselves a part of the future district heating socio-technical network. This suggests that practitioners are not just 'for' or 'against' alternative futures (Kemp and Loorbach 2003; Bergek et al. 2008), but are rather acting today to economize their future. This may have a bearing in terms of the dualism between incumbents and challengers; it may stimulate a move away from the simplistic dualism and open a new line of inquiry regarding how and who has the capacity to economize their future and, hence, take part in energy transition processes.

CHAPTER 7. ALBERTSLUND FORSYNING: TRANSITIONING FROM A ‘TRADITIONAL’ TO A ‘4GDH’ DISTRICT HEATING GRID

This chapter investigates how the municipal district heating utility Albertslund Forsyning mobilizes its socio-technical network to achieve a low-carbon transition. It follows the attempt of the western utility (receiving its heat from VEKS) to transition its infrastructure from a ‘traditional’ grid into a so-called ‘4th Generation DH grid” (4GDH). As seen in the literature review in Chapter 2, the idea of the 4GDH is to create synergies between the multiple components of the DH grid. It is asserted in the engineering literature that such a transformation requires significant reconfigurations of the infrastructure (low supply and return temperature, low heat consumption, well-insulated households, low-temperature energy sources, etc.) (Lund et al. 2014).

As advocated by the theoretical contributions informing this inquiry, understanding where Albertslund comes from is a prerequisite to understanding its agency (Asdal 2012). Therefore, this chapter opens with an investigation of the past urban and political developments of the municipality. This paves the way for the second section, which focuses on Albertslund Forsyning contemporary challenges and room for action. Finally, the third section follows the work of the utility and the role of material devices in their attempt to transform the grid from a traditional to a 4GDH grid. This last part is, therefore, the one that examines in detail the actions being performed, which material devices are mobilized, by whom, and with what effects. It is, consequently, the most extensive section of this chapter.

7.1. ALBERTSLUND, “THE TOWN OF PLANS”

District heating infrastructures are greatly influenced by their municipal material fabric (because of the building stock’s properties, the layout of the city, etc.). Therefore, in order to understand Albertslund Forsyning agency, one must explore the urban fabric of its municipality. This section thus investigates Albertslund’s evolutions in two parts: first, the perception of it as a ‘pioneering’ municipality, which soon began to waver, and second, the efforts of the municipality to revitalize the urban and social fabric.

7.1.1. THE RISE (AND FALL?) OF A PIONEERING MUNICIPALITY

After the World War II, Denmark's population grew rapidly, and Copenhagen started to become congested. As an answer to these density problems, the Copenhagen Regional Planning Committee established a regional plan in 1947, known as the Finger Plan, which constructed five suburban train lines along which new municipalities were to be developed to relieve some of the pressure on Copenhagen. The plan would permit the construction of new housing and control regional urban sprawling. The township of Herstederne was identified in the Finger Plan as one of the satellite cities to be constructed along with one of these five train lines (Frandsen, Ott, and Nielsen 2019).

As the population was increasing faster than expected, in the 1970s, the Ministry of Interior and Health also implemented the 'Municipal Reform' (da. *Kommunalreform*), which reduced the number of parish municipalities from approximately 1,300 to 275, while at the same time decentralizing some governmental responsibilities to the municipalities (Danish Ministry of Interior and Health 2005). The townships Herstederne, Harrestrup, Vridsløselille, and Risby were merged and became Albertslund Municipality in 1973 (Frandsen, Ott, and Nielsen 2019).

The municipality of Albertslund was designated in the Finger Plan to welcome up to 40.000 inhabitants. The city council, led by the Social Democrats, foresaw the construction of a high percentage of social housing to welcome low or medium income residents (Héland 2005).

The urban planner in charge of the Finger Plan, Peter Bredsdorff, together with the architect Knud Svensson, was also in charge of the development of Albertslund Municipality. The two practitioners were compelled to build the municipality rapidly due to the pressing need for housing. Consequently, they decided to design a city according to a grid-like plan and to use pre-fabricated houses to expand the city rapidly and to standardize the quality of the houses at affordable prices (Héland 2005). The prefabricated houses are, therefore, similar in terms of their architectural and material composition. Within 10 years, the entire city had been almost completely constructed. Figure 10 illustrates the local plan designed by Peter Bredsdorff and Figure 11 a bird's eye view of the city once it had been built:

Figure 10: Local Plan of Albertslund South, designed by Peter Bredsdorff. (Frandsen, Ott, and Nielsen 2019).

Figure 11: Bird's eye view of Albertslund South in the 1970s. (Albertslund Posten 2015).

The grid-like plan is clear in the two illustrations, but what might not be is that the prefabricated houses are low-rise, each with their own small garden and with common areas for every 5-6 homes. The architecture is designed to contrast with Copenhagen's 1930-40s block edifices and the post-war high-rise buildings; a contrast considered by the public and urban architects as representing pioneering city planning (Héland 2005; Frandsen, Ott, and Nielsen 2019).

Furthermore, the social democratic city council had the ambition to experiment with other aspects of the municipality. For example, they decided to try an idealized zonal urban model, which separated recreational, housing and industrial/commercial areas, and separated waste and rainwater infrastructure, making Albertslund one of the first Danish municipalities to experiment with the infrastructural divide (Héland 2005).

Another experiment was the innovative bike path system: a structure combining small tunnels and separate bike and car lanes, which improved the safety of cyclists (Albertslund Municipality 2020a). Overall, the city council was driven by the ambition to construct an experimental municipality (Elle 2001) and to "*found a city with a good family environment where young incomers from Copenhagen can benefit from more light, air and welfare"* (Albertslund Municipality 2015, 5), thereby reducing congestion in Copenhagen municipality. The idea was to create a good and cultural environment for children and teenagers to attract young adults from Copenhagen eager to have more space while having access to the capital's job market thanks to the suburban train line. Soon, the nickname "the Town of Plans" was being used to refer to Albertslund: nothing was left to chance (Elle 2001). Christian Clausen, resident of Albertslund since 1978, relates the following about his experience:

> I can clearly remember that when our children were growing up, many families were saying, "*We would like to move out and buy our own home*" because it was mostly rental housing, "*but we can't because our children don't want to leave*!" (*laughter*). There was a child-friendly environment because Albertslund Municipality had prioritized it. It is probably not the only reason why, but the city is characterized by social democratic ideas, and they put a lot of emphasis on the well-being of kids, young people, and culture (Int. Clausen, my translation).

Considering the families' reactions as related by Christian Clausen, it seems that Albertslund's ambition to become a city for young families with children had beensuccessful.

These socio-democratic premises did not disappear from the political agenda and the first mayor, Finn Åberg, was rewarded for it. With strong citizen support, Finn Åberg remained mayor for 31 years. His son, Hjalte Åberg, had also been involved in municipal political life as chairman of the environment and planning committee during a mandate, which suggests strong – and maybe slightly loyal – lasting political stability in the municipality. The current mayor, Steen Christiansen, is also a socio-democrat and has had the position since 2010.

However, in the 1990-2000s, Albertslund's social and urban fabric became tarnished due to a combination of two main factors. The first was rooted in Danish immigration and labor market politics; in the late 1960s, Denmark opened its national borders to attract labor from Turkey, Pakistan, and Yugoslavia (Danmarkshistorien.dk 2020). The availability of affordable social housings, together with access to public transport, attracted a great number of immigrants to Albertslund. By the 1990s, the percentage of immigrants had reached 20% of the municipality's inhabitants and, by 2005, in some areas of the municipality, 64% of the inhabitants had an ethnic background other than Danish – immigrants who experienced difficulty integrating into the municipal life (Héland 2005). In 2005, 15-20% of the residents relied on social assistance and, gradually, Albertslund became perceived as a ghetto city. This created a social divide and tarnished its reputation as a family environment (S. H. Nielsen 2005). The city council was recognized as being subject to "*hard social problems*" (S. H. Nielsen 2005) and, in 2010, it was put on the national "Ghetto list" (Jørgenssen 2013).

A second factor is the endurance of the prefabricated houses. Built quickly to respond to the demographic pressure, the municipality used prefabricated houses which did not appear to be particularly well suited to the wet Danish weather conditions. Problems with humidity and mold emerged across the city to such an extent that engineers and architects asserted that "*it would be with no doubt more economically beneficial to tear down the houses and build new ones*" rather than to renovate them (Hedehus, in U. Andersen 2008). Gradually, the image of the prefabricated houses altered from being seen as pioneer housing to poorly insulated buildings (Héland 2005).

7.1.2. REVITALIZING THE MUNICIPALITY

As seen in Chapter 5, environmental issues were becoming a collective concern in Denmark and internationally in the 1990s and 2000s. The first Climate Summit and a succession of ecological disasters thrust environmental matters into spotlight. Albertslund's city council mobilized these ecological concerns as a means of creating a new urban future in which the environment was given predominant importance, while simultaneously solving the municipality's emerging problems. However, given the lack of municipal economic resources and state support, the municipality had to rely on voluntary and collaborative green approaches, and, for that purpose, it launched a series of initiatives (Coenen 2009).

For example, in 1992, Albertslund was the first city in Denmark to implement Green Accounting to reduce the environmental impact of companies and industries (Elle 2001). A few years later in 1995, Albertslund launched its Agenda 21 (the action plan of the United Nations towards sustainable development), even before it was stipulated by the Danish Ministry of the Environment (Gram-Hanssen 2000). The Agenda 21 was accompanied by the creation of the "Agenda Center 21" in 1996 – an organization administered by the municipality but physically detached from it, staffed by experts and volunteers whose tasks were, and still are, to support and advise associations, groups, and residents in their environmental efforts (Agendacenter.dk 2015). The projects conducted by the Agenda Center encompassed a diverse range of activities such as organic community gardens, photovoltaic panel demonstrations, waste sorting, tree planting, educational events, etc. (Agendacenter.dk 2020).

The results of the Green Accounting and Agenda 21 initiatives became quickly visible in the municipality, both in terms of environmental accomplishments and social relations. In the ten following years, waste recycling doubled, CO2 emissions were cut by 40%, and water consumption was almost halved (Héland 2005). The results were also long-lasting. Fifteen years later, Albertslund was still the Danish municipality with the lowest water consumption (Erlitz 2017). And besides, citizen participation organized around the environmental and new collective city management recreated a sense of municipal belonging (Coenen 2009).

These environmental and social successes were also supported by a new form of democratic collective participation proposed by the city council. Finn Åberg, the mayor, invited the inhabitants to have a direct voice in the city hall regarding infrastructural and environmental matters through "The User Group", created in the 1980s. Steen Westring, current director of the district heating utility, Albertslund Forsyning, explains:

> The User Group is a very special phenomenon, which, to my knowledge, exists only in Albertslund. 60 representatives have been elected to be part of the User Group (...). The User Group meets 4 times a year, and it is in reality those who have the right to designate what the municipal council should discuss. In other words, they can come up with some thoughts and suggestions which the municipal council must then put on the agenda. (Int. Westring, my translation)

The user group is consulted on all matters of environmental importance before they can be validated by the city council (Albertslund Municipality 2020a). The Group has thus a significant influence on the decision-making process of the municipality, because the city council needs the User Group's approval of project proposals and their budgets. The tone and atmosphere of the meetings display a keen collaboration between the citizens and the politicians; the mayor knows the names of the representatives, the tone is cheerful, there are no significative arguments but rather detailed questions about the budgets, timelines, and environmental benefits of the proposed plans (field observation, 05/03/20). It appears that the User Group is a means of strengthening the political-public dialogue and to disseminate information about the municipal agenda while ensuring public support (Læssøe 2007).

The city hall also intended to revitalize social ties through culture. A concrete example is Bakkenshjerte, a cultural place created by the municipality and dedicated to the 10 to 18-year-olds across socio-professional categories and ethnic backgrounds. For a modest sum (6.5€ a month), the municipality provide access to a place where young people could meet, exchange, and experience musical activities (how to play the guitar, the keyboard, or to rap (Bakkenshjerte.dk 2020)). The cultural place is considered by the city council as a bridge between the different nationalities and as a means of increasing social cohesion. Today, the well-known rap-musicians Suspekt, Anders Matthesen, and Fouli say that they are proud of having started their music carrier at Bakkenshjerte and describe themselves as being "*products of Albertslund*", despite the "*culture schock*" as a kid and the ghetto label that was attached to the municipality (Karl 2020).

Over the years, Albertslund has continued to experiment with different environmental solutions collectively and, in its 2016-2025 municipal strategy, aims to build "*the city as a laboratory*" (Albertslund Municipality 2015, 6). The municipality has been keen to establish professional and academic collaboration, which resulted in its inclusion in various experimental projects such as 'Lightning Metropolis' and 'DOLL Living Labs' (Albertslund Municipality 2020c), both of which aimed to reduce energy consumption, or as 'Energi På Tværs' (cf. §5.x.x, inter-municipal cooperation for a future energy system) or again as the 'LINC projekt' (experimenting with self-driving buses for collective transport (Albertslund Municipality 2019)).

Over the years, the perception of Albertslund as an innovative and environmentally friendly municipality stabilized across the region. This perception materialized in the political discourse as well in the newspapers. For example, in 2009, the Minister of Climate and Energy, Connie Hedegaard, nominated Albertslund as one of the Danish 'Energy Cities', appointed to inspire other cities to implement climate and energy initiatives (*Sn.Dk* 2009). Moreover, Albertslund has been regularly referred to as an innovative city in the professional and regional newspapers (Pedersen 2011; *Vestegnen* 2013; Erlitz 2017). This political and professional recognition prompts frequent visits from universities, energy consultancies, and energy utilities, eager to learn from the acclaimed environmental and innovative municipality (Int. Hansen and Andersen).

These changing socio-urban conditions have had a different bearing on Albertslund Forsyning. Albertslund's urban fabric and social development have emerged from the ambition to create a pioneering environment for young families to unclog Copenhagen but have eventually led to poor building stock of prefabricated houses. This leads to a paradoxical situation for the municipality, which, one the one hand, wants to be a pioneer, and on the other, has a declining building mass with a high heat consumption. However, in the following section, we will see that the emphasis placed on the environment and public participation by the city council has had consequences for Albertslund Forsyning's agency.

7.2. ALBERTSLUND FORSYNING

The following sections examine the consequences of these socio-urban factors discussed above for Albertslund Forsyning. The first section explores how the urban fabric currently challenges the utility for many reasons, while the second explores how the utility, despite the challenges, finds agency to reconfigure the DH system from traditional to 4GDH.

7.2.1. ALBERTSLUND FORSYNING AND THE URBAN CONSTRAINTS

Albertslund Forsyning was established in 1964. Its creation went hand in hand with the expectation of welcoming up to 40,000 residents, as designated by the Finger Plan.

Originally, the utility intended to produce and supply heat to its inhabitants from six oil boilers, but after the oil crisis and the establishment of the regional transmission infrastructure, the responsibility of generating heat was delegated to the transmission companies. The mayor of Albertslund, Finn Åberg, was known as a DH enthusiast and was even politically involved in the creation of the transmission company VEKS.

Albertslund Forsyning thus stopped being responsible for the heat production in 1983 and started to lease, on an annual basis, its production units to VEKS. Since then, Albertslund Forsyning has bought its heat from VEKS and is responsible for the municipal heat distribution, and the utility is held accountable for the share of the regional DH system it consumes. This means that the more Albertslund Forsyning buys from VEKS for Albertslund residents, the more Albertslund Forsyning's share of carbon and other environmental emissions increases (CTR, HOFOR, and VEKS 2020).

Even though Albertslund Forsyning have not had to produce heat since 1983, they nevertheless face challenges on several counts. Firstly, there is the issue of the deteriorating buildings. Due to the poor insulation and quality of the urban fabric, the residents tend to have high heat consumption to balance the heat losses and maintain a sufficient indoor temperature.

Secondly, although many dwellings have been renovated over the years, the renovation projects did not include renovating the households' heating system. Peter D. Andersen, an energy consultant at Albertslund Forsyning, relates that "*often, [the inhabitants] have discarded the radiators from their kitchen because it had to look neat"* (Int. Andersen, my translation). He further explains that removing one or two radiators from a household can have a tremendous impact on one's heat consumption. He clarifies that the reason is that the heat delivered is a function of the temperature difference between the radiator and the temperature in the room. When a room needs more heat, the heat flow in the radiator increases, thereby increasing the radiator temperature and, thus, increasing the temperature difference between the radiator and the indoor temperature. If the radiator is too small or if there is only one instead of five, the radiator needs to have a high heat flow to increase the temperature difference with the indoor temperature. In other words, using one radiator alone is much less efficient than using five and, consequently, the dwellings which have discarded radiators consume more heat. This, in combination with the fact that the building mass is badly insulated, means that Albertslund dwellings consume a relatively high amount of heat.

Thirdly, the grid-like urban planning of the city, originally thought of as a means to achieve rapid urban extension, is currently challenging the heat delivery. The spread layout of the city, illustrated in Figure 10 and 11

Figure 10 above, means that the heat must travel through a branched and aged DH pipe network to supply each individual heat substation. Steen Westring, the director of Albertslund Forsyning, explains:

> [We have] a significant heat loss. Right now, we have a heat loss of around 20%. It is a lot. And that is because Albertslund is special. (…) One thing is that the district heating network is old, and the other is that it is a very branched district heating network. (Int. Westring, my translation)

The heat losses mean that Albertslund Forsyning is compelled to buy, on average, 20% more heat than the amount consumed by the residents. However, despite facing these multiple challenges, the utility can find agency in its organizational structure.

7.2.2. ALBERTSLUND FORSYNING ORGANIZATION

Albertslund Forsyning is one of seven Danish DH utilities and is 100% municipality owned (Int. Westring). In Denmark, most of the DH utilities are either "consumer-owned" or "limited companies", which means that they are institutions on their own. In Steen Westring's words, this implies that Albertslund's mayor is a "*municipal director*" responsible for the approx. 2,000 employees of the municipality and for politically steering the strategies for the different public infrastructure (waste, lighting, transport, district heating, etc.). Furthermore, according to Hans-Henrik Høg (former director of Albertslund Forsyning and currently chief of the municipal administration for technology and the environment), the current 'municipal director', Steen Christiansen, shares the same particular interest for DH as his predecessor, Finn Åberg, which is also reflected in his running and election as VEKS's chairman (Int. with Høg, VEKS 2020a).

Being 100% municipality-owned implies that the tasks of developing a heat strategy, establishing a project proposal, and approving the proposals, are all carried out by different departments of the municipality. Steen Westring, director of Albertslund Forsyning, relates:

> There is a little difference in being a municipally owned utility company, because the city mayor is the head of the utility. It is a bit interesting for Albertslund Forsyning because (…) the municipal board members are the ones who decide everything. There is, in that sense, political management of the municipality. (Int. Westring, my translation)

This concretely means that Albertslund city council establishes a heating strategy, Albertslund Forsyning (owned by the municipality) develops a project proposal, and finally, the Technical and Environmental department approves (or amends) the proposal. The fact that the different departments that carry out the heat planning tasks are all managed by the same city hall is said to create a convergence between the political interests and the operation of the utility (DEA 2016, 42). However, as seen above, in Albertslund, every project proposal must first be approved by the User Group before it can be validated by the municipality. Consequently, this implies that when Albertslund Forsyning has a project proposal, it is first presented to the User Group, who can amend or validate it, before it is sent to the city council (Læssøe 2007).

Albertslund Forsyning is a 'regular' middle size DH utility; it employs about 20 people, who work as secretaries, project leaders, and technicians. Among these employees, Albertslund Forsyning has however one organizational specificity; it has a dedicated task force called the 'Energy Team', which was created in the 2000s. Hans-Henrik Høg, the former director of the utility, describes it as follows:

> [The Energy Team] works closely with the citizens. The rest of the utility's work is more traditional; they secure the distribution, they lay down new pipes, they ensure good finances, the classic tasks… But what the Energy Team does, it is probably a little more… Albertslundish! (Int. Høg, my translation)

The Energy Team is currently staffed by three employees and has, in the last 20 years, been tasked with working together with the inhabitants of Albertslund to reduce their heat consumption. The task force has been dedicating its time to providing energy advice, disseminating knowledge about energy renovations as well as supporting dwellings in operating their heat systems appropriately. They have, therefore, been in regular contact with the residents and with the User Group representatives.

Furthermore, as the city hall has put environmental matters on the agenda, and as the residents have been keen to support these developments collaboratively, it appears that the organizational structure provides a form of decision stability and strength, which ensures the approval of the citizens and supports environmental progress.

7.2.3. SUMMARY

Albertslund Forsyning appears to be, on the one hand, greatly constrained by the urban fabric and by the nature of the households' renovations, and on the other hand, to have a past, political and organizational association that provides strong support for enforcing environmental and experimental project proposals. These conditions, part of the socio-technical network in which the utility finds itself, seem to both challenge Albertslund Forsyning and give it a certain capacity for action. The following section follows how the utility is using this configuration to assemble a "4th generation district heating" grid.

7.3. ASSEMBLING A 4TH GENERATION DISTRICT HEATING TRANSITION

This section follows the work of the municipal DH utility, and more specifically, the Energy Team, in their attempts to transition the municipal DH grid from a traditional into a so-called '4th Generation DH grid'. It explores what it takes for Albertslund Forsyning to construct a DH strategy and to pull together its resources to achieve the energy transition. This section, therefore, delves into the creation and effects of different material devices amid Albertslund's transitioning process.

The first section begins by discussing the establishment of Albertslund Forsyning's project proposal for achieving carbon neutrality by 2025. The second section follows the establishment of two material devices that are reconfiguring Albertslund Forsyning's agency, namely, new Smart Meters and 'TAO Agreements'. The third section follows the Energy Team's work and the mobilization of other material devices in their aim to make, respectively, heat renovations and heat consumption visible to Albertslund Forsyning's heat customers.

7.3.1. PROJECT PROPOSAL

In 2015, Albertslund's city council launched the municipal goal of becoming carbon neutral by 2025. The strategy stipulated:

> We set the goal of having a CO2-neutral electricity and district heating supply by 2025. (...) We will work with heat planning and with the development of a service for households as an alternative to individual oil or natural gas-based heating. We will secure that Albertslund Forsyning delivers only low-temperature district heating. We will work with strategy energy planning, and we will gradually identify the possibilities for local and renewable energy production. And we will work with the development of a smart energy system – also called Smart Grid – as a way to supply a sustainable, economical and secure energy supply in Albertslund. Albertslund will become the prototype of the modern city developing holistic solutions. (Albertslund Municipality 2015, 21, my translation)

The city council thus gave Albertslund Forsyning ten years to achieve carbon neutrality. Niels Hansen, a special consultant at Albertslund Forsyning since 2007, relates his surprise when the city council asked the utility to become carbon neutral:

> My colleagues came back [from a municipal board meeting] and said: "*Now our electricity and heat supply has to be CO2-neutral by 2025!*". At that time, people were talking about 2035, so it was 10 years earlier than the other municipalities. But I said: "*What are you talking about?*", because we don't produce electricity or heat, and it depends on whether

> VEKS delivers CO2 neutral heat. (...) And then I thought: "*Ok politicians, you have said this. But do you really mean it?*", and we wrote '4th Generation District Heating' [in Albertslund Forsyning's strategy], because I think it is the way for having a carbon neutral DH. And it was 'accepted' without any problems. I was quite surprised that they accepted it. And then we discussed it with the User Group, and afterwards with the municipal board. And when the board took it, they had no remarks!! (*Laughter*). There was no discussion about it! (Int. Hansen, my translation)

Niels Hansen's surprise is related to the transformations required to convert a district heating grid with high heat losses and high heat consumption into a 4^{th} Generation DH. It is not just a matter of implementing the technology, but rather a matter of transforming the entire heat distribution and consumption chain: insulating the dwellings, fixing the dwellings' heat systems, establishing new shunt pumps, integrating local energy sources, etc. (Lund et al. 2014). Albertslund Forsyning's first assignment was to write the 4^{th} Generation DH project proposal, which was then to be submitted to the User Group, and then later to the Technical and Environmental department – a project proposal that was accepted in both instances.

According to Niels Hansen, one of the reasons why the 4th Generation DH agenda was accepted by the city council is probably because it is "*a socialist municipality*", and that "*there are no liberal politicians to say that it is too expensive*" to conduct such a transformative project. According to Niels Hansen, implementing a 4^{th} Generation DH strategy was a way for the city hall to revitalize the urban fabric:

> The idea is (…) to make better households, from ghetto to modern buildings, because that is what it is about for the municipality, for the politicians and for the inhabitants. (Int. Hansen, my translation)

It appears that the targeted "*4^{th} generation DH*" that "*people talk about*" (Int. Westring) was perceived by the city hall as a way of restoring the declining building mass and the regional perception of Albertslund as a pioneering municipality. This is also supported by Hans Henrik Høg (Albertslund Forsyning's former director) who adds that the energy regulation[14] stipulates that all energy suppliers in Denmark must reduce their energy consumption/distribution by 1-2% per year, and that:

> Energy companies can buy energy savings on a market. But in Albertslund, we have decided that all the savings must be achieved within the municipal borders. (...) In that way, we give some money to our own inhabitants, and we also give them advice, which supports them. This ensures that the private households also come along in the green wave. (Int. Høg, my translation)

[14] The Energy Saving Order nr. 864.

This confirms the city hall's desire to revitalize Albertslund's building mass and to pursue being an environmentally friendly city. Furthermore, according to Høg, the longstanding experimental and environmental efforts of the citizens facilitated the User Group's approval. Niels Hansen also supports this perception and recalls that the User Group had no objections to the project proposal, instead they appeared keen to be part of the project.

A year after the publication of the municipal strategy, Albertslund Forsyning's project proposal was accepted by both the User Group and the city hall. The utility then sent a letter to all the inhabitants, informing them that in fewer than 10 years, the temperature of the heat supply would decrease from 95°C to 60°C, and that all the households should be ready for such a change. Hans Henrik Høg relates:

> We wrote to all our inhabitants in the municipality that, within 10 years, they have to be ready for us to reduce the heat supply temperature. '*It means that you have to get started, to do something with your insulation or to put up an extra radiator or do something*'. (Int. Høg, my translation)

The letter explained that the inhabitants would most probably have to energy renovate their home in order to accommodate the temperature difference in the heat supply, in which case the utility would offer its expertise and administrative support, as well as a limited financial contribution. Ironically, although the utility feared receiving complains, the only replies were from a few inhabitants wondering why they received the letter twice and not just once.

The following section focuses on how the Energy Team has, since the letter, been working on transforming Albertslund's DH grid from a traditional to a 4th generation DH grid.

7.3.2. MATERIAL DEVICES RECONFIGURING THE UTILITY

This section follows the establishment of two new devices by Albertslund Forsyning, namely, Smart Meters and TAO Agreements. It reveals how the two new devices give Albertslund Forsyning a new capacity for action to assemble the '4GDH' strategy

7.3.2.1 Smart Meters

As mentioned above, since its formation, the Energy Team's principal task has been, and still is today, to support the heat customers in conducting energy renovations. To this end, the task force regularly called dwellings based on their assumptions as to which buildings were the least energy efficient, as well as received calls from heat customers asking for heat advice. The Energy Team provided technical support and informed their customers about the long-term earnings prompted by different energy renovations. Furthermore, the utility financed about 5-10% of the renovation projects, and they informed the heat customers about subsidies provided by the Government.

The remaining money had to be invested by the inhabitants themselves. In other words, the Energy Team's main task was to make visible and to support heat renovation projects technically and to some extent economically.

However, until then, the utility had provided this service to its customers without being able to identify which houses were actually in need of energy renovations. In order to target their counseling more accurately, Albertslund Forsyning, therefore, installed new smart meters in the DH grid in 2018 as part of the 4th generation DH strategy. Peter D. Andersen, an energy consultant in the Energy Team, relates:

> We changed all the meters last year, now there is an hourly reading. It's quite nuanced. (…) I look at the district heating data, and I can use it to find the places where it makes the most sense to do something. (Int. Andersen, my translation)

These new technical devices revealed abnormal heat consumption patterns and, thereby, provided new information to the utility. The smart meters thus enabled the Energy Team to detect which buildings had significant heat consumption (often referred to as 'critical heat customers' by the professionals), which in turn, allowed them to tailor their counseling approach.

It can be argued that the Smart Meters are equipping the utility: it provides them with a new capacity for action. The meters reconfigure the Energy Team's agency by enabling them to prioritize their energy counseling and adjust the previous shortcoming of not being able to detect irregular heat consumptions.

7.3.2.2 TAO Agreements

In 2017, Albertslund Forsyning started to offer a new service to its customers called the 'TAO Agreements'. TAO is short for "*TilslutningsAnlægs Overtagelse*", literally "Connection Unit Takeover". The TAO agreement is a service proposed by the utility to the heat customers of Albertslund in which the utility replaces their old heat unit connection with a new one. The utility then owns the unit and rents it out to the customers on a monthly basis. The heating unit is, technologically speaking, similar to the previous one, but it is owned differently. Steen Westring, Albertslund Forsyning's current director, explains:

> In most places, people own their DH connection unit. The trick here is that we can displace our supply limit and lease the connection system to the customers, because it is cheaper for them. (…) For example, we have investigated that in Albertslund, if you live in a detached house of 130 square meters and need a new connection unit because the old one is obsolete, maybe it is 20 or 30 years old, it will cost you about 40,000kr (…). What we offer is, therefore, to pay it for you, and then you reimburse us over the next 20 years. (Int. Westring, my translation)

As explained by the director, the TAO agreements allow the utility's supply boundary to be moved over to the customers' heating units. For the utility, it is a way of ensuring that the customers' heating units function as they are supposed to and that the radiators are used properly, thereby providing optimal heat supply. For the customers, it is a way to avoid investment and maintenance costs as well as the related operation responsibilities. It is also a way to ensure an efficient heat consumption and, thus, a lower heating bill. The customers who sign a TAO Agreement still have control over their indoor comfort, but the utility has pushed their infrastructural boundary from stopping at the building's main valve to inside the buildings, as Albertslund Forsyning illustrates in their prospectus, Figure 12.

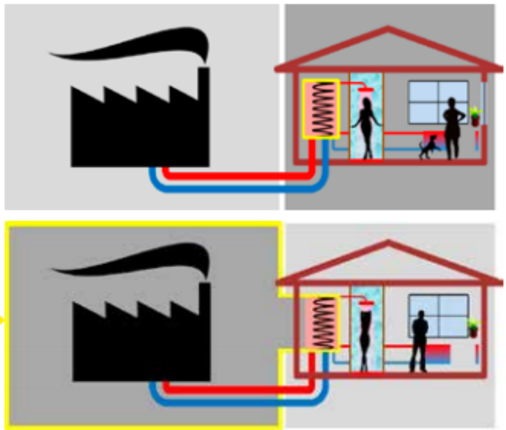

Figure 12: TAO illustration from Albertslund Forsyning (2018).

However, the utility needs an additional component for the TAO service to work. Steen Westring explains that the agreement also requires the installation of thermostatic valves in the dwellings' radiators. He explains:

> Most of the houses were built in the 70s, and (…) that means the radiators are big because they have had to be able to cope with the heat losses. But as we are now lowering the temperature, the capacity of the radiator will be significantly reduced. (...) By installing new thermostat valves, we can ensure that there will be a sufficient heat supply flow in all the dwellings' radiators. (Int. Westring, my translation)

He then continued to explain that reducing the supply temperature from 95°C to 60°C necessitates increasing the heat supply flow in order to maintain a sufficiently high heat delivery. As the heat delivered is a function of the temperature difference between the radiator and the indoor temperature, reducing the heat supply temperature entails increasing the heat supply flow to maintain a sufficient temperature difference between the radiator and the indoor environment. The thermostatic valves are a material device that regulate the flow and, consequently, ensure an appropriate heat delivery, even with a lower heat supply temperature.

To summarize, it takes a combination of devices to enable the TAO Agreements to operate: a signed contract between the utility and customer, a newly installed heating unit (which is a similar technology to the previous one but is owned by Albertslund Forsyning), and the thermostatic valves. It can be argued that the contracts are literary inscription devices, defining the rules of exchange between the consumers and the utility. The contracts facilitate an extension of the utility's chain of action without having to resort to the implementation of new technology, but instead by repositioning its boundary from before to after the households' heat connection. In a way, the contracts enable the utility to expand its infrastructure from within by integrating elements that had traditionally been excluded from its agency. The contracts simultaneously render the heat customers passive; even if they can still control the indoor temperature, they are passive in terms of the maintenance and operation of the heat units.

The replaced heating unit and the thermostatic valves are technical devices enabling a new operation of the heat provision. The two devices are not 'new' or 'pioneering' but, in combination with the contracts, they afford a new capacity of action to Albertslund Forsyning. Altogether, these three devices enable the utility to ensure an optimized heat provision to the heat customers.

The success of the TAO, therefore, appears to be contingent on its distributiveness; it is the articulation of the contracts with two material devices that paves the way for preparing the building mass to receive a lower heat supply, as targeted by Albertslund Forsyning's 4th generation DH strategy.

7.3.3. MAKING HEAT(S) VISIBLE TO THE CUSTOMERS

Since 2017, the Energy Team has also been working on making heat(s) visible - heat(s) in plural to signify the work of the utility in making both the buildings' heat renovation needs/solutions visible, and the customers' heat consumption visible. Because the Energy Team does not have the agency to carry out energy renovations themselves or reduce the customers' heat consumption, making the heat(s) visible is their attempt to modify both.

The following sections investigate the two approaches of the utility. The first section follows the work of the Energy Team in their attempt to reach as many customers as possible by disseminating general heat renovation information with the creation of two new devices, namely, a digital map and a catalog. The second section follows the Energy Team's work of making the heat customers' consumption visible through the introduction of two more new devices, namely, a modified heat bill and a SmartApp. Last but not least, the section concludes by discussing how the Energy Team enables the circulation of money for energy renovation projects, as well as how they mobilize Albertslund's social ties to disseminate energy knowledge. The sections analyze how the devices have different effects on the heat customers.

7.3.3.1 Heat renovations: Maps, catalogs, and money flows

Maps

As seen above, the implementation of the Smart Meters in 2018 revealed which buildings have abnormally high heat consumption. However, these devices did not make the reasons behind this high consumption visible. The Energy Team was still uninformed about the actual status of the buildings' composition, i.e., which renovations projects had been carried where and what the results were. How many radiators had been discarded, which heat customers had carried out renovations, and which households were just consuming a lot of heat? These were the questions the Energy Teams needed to answer when preparing the building mass to receive a low heat supply temperature, as part of the 4th Generation DH strategy.

To assess the need for energy renovations, Peter D. Andersen, a member of the Energy Team, spent about a year screening the composition of Albertslund's urban fabric. He relates:

> I was out measuring the radiators, looking at the insulation of the buildings, etc. I did some investigations on the residential areas, pretty much all of them. (Int. Andersen, my translation)

He explains that, in the course of one year, he spent 1/3 of his working hours visiting people's houses, measuring the windows, the radiators, checking the insulation, etc. Each time he gathered information about one home or building, he passed it on to another employee from the utility, who would transfer the data into Geographic Information Software (GIS). If making appointments with the inhabitants and measuring the urban composition took some time, Peter D. Andersen relates that, overall, gaining access to the dwellings was "*rather easy*". According to the members of the Energy Team, being a non-profit utility creates a certain amount of trust with the inhabitants. They explain that the counseling they provide is impartial in comparison to HVAC and architects who have an economic interest in selling products. The Energy Team suggested that this position makes them more legitimate and trustworthy in the eyes of the residents, who, in turn, appeared more inclined to listen and implement the Team's recommendations.

After a year of data collection and programming, the notes were translated into a comprehensive digital map, after which, the utility created the website *60grader.albertslund.dk* (literally "60 degrees Albertslund", referring to the 60°C heat supply to be attained by 2026) on which the map was posted, as well as complementary information about the reasons why the utility had the goal of lowering the supply temperature. The website also showcases in short video clips some of the successful renovations that have already been carried out on some dwellings, extolling the improved indoor climate and financial gains. Figure 13 is a snapshot of the map, which can be found on the created webpage.

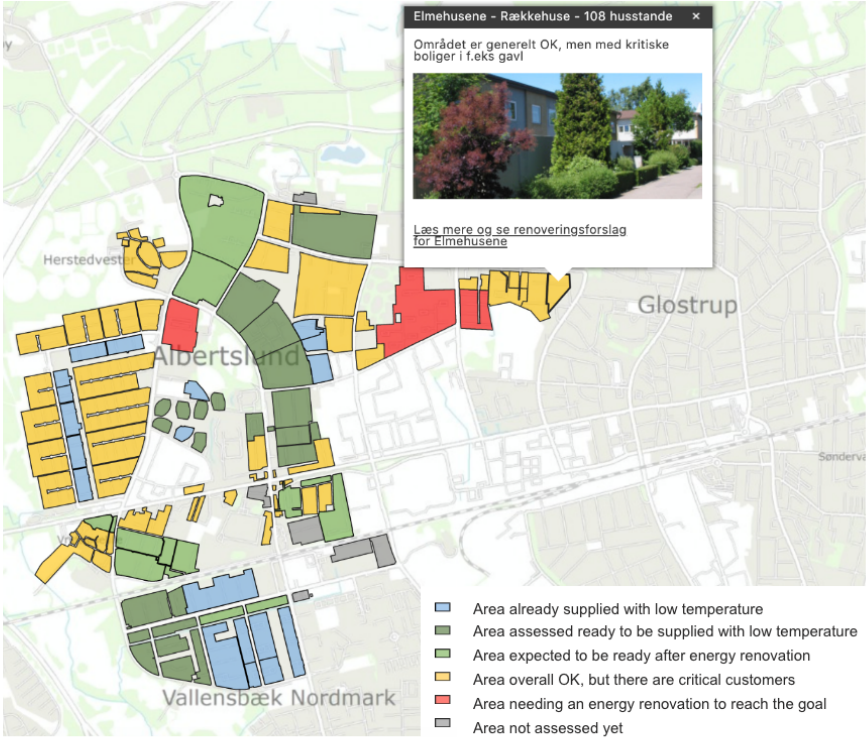

Figure 13: Snapshot of Albertslund mapping (accessed 18.11.20 on 60grader.albertslund.dk)

The Energy Team took advantage of the prefabricated homes, which, as seen above, are similar in their architectural and material composition. This has enabled the Energy Team to abstract the individual measures collected by Peter D. Andersen at the housing block level. One can then click on one of the housing blocks on the website and see what renovations have been carried out. For example, on the website, one can read that Elmehusene is an area of 106 townhouses considered unfit for a 60 degrees district heat supply. The area is considered as being "*overall OK but with critical buildings*". Also, a linked webpage to renovation proposals provides information about the renovations to be carried out: replacing the windows and doors, re-insulating the gables, and modifying the ventilation system are the three most important renovations that the Energy Team advises to do. Furthermore, the website provides information about the costs of each renovation, disseminates knowledge from the State Building Research Institute, and showcases one renovated household. Niels Hansen, a member of the Energy Team, relates:

> The idea with [the map] is that you could share experiences (...) and have easy access to what [energy renovation] makes sense and what to focus on. [The map] makes knowledge visible. (Int. Hansen, my translation)

This map can circulate among the heat customers and makes heat renovation needs visible. It can thus be qualified as being an inscription device in the sense that it packs the world into an illustration. The map has then two effects: it enables the Energy Team to tailor their energy counseling, and it reconfigures the heat customers' capacity to act by making knowledge visible.

Catalog

The utility also plans to use the measurements collected at the dwellings in another form. Steen Westring relates:

> The idea is to make a catalog. We are in the process of finding 10, 20 similar standard detached houses (…) and to provide suggestions about how to renovate them to prepare them for a low-temperature heat supply (…). We will have multiple cases, provide support and help, descriptions of, for example, the ceiling insulation (…), some cost indications, some guidelines about how to do the renovations, what to be aware of, … (Int. Westring, my translation)

Instead of having "*everyone go to their own architect, the idea is to make common solutions and to preserve the homogeneity of the neighborhood*", adds Niels Hansen (my translation). Using the homogeneous building composition resulting from the early municipal developments of the 1980s, the Energy Team can generate standardized knowledge from situated energy renovations. By sharing know-how and finding best-case renovation solutions within a homogeneous neighborhood, the utility and the inhabitants can both save a time-consuming activity and preserve the uniformity of the municipality.

The catalog is, therefore, an inscription device *in the making*: it is yet to be developed, but its aim is to translate the building composition measurements into a comprehensive outlook. It will make visible which concrete renovations can be made, how, and at what price. Its circulation amongst the heat customers may encourage them to carry out energy renovations and reconfigure their capacity to act.

Financial flows and social ties

Another part of the Energy Team's work consists of highlighting to the inhabitants which subsidies can be claimed for heat renovations. As a utility, Albertslund Forsyning can finance about 5-10% of heat renovations projects. Therefore, despite having the economic means (and responsibility) to cover the customers' heat renovations, the utility signals which financial flows are possible to support the energy retrofits. The utility intends to use the website and the catalog to make visible which subsidies, grants, or possible tax reductions are available to encourage the heat customers to initiate energy renovations. Peter D. Andersen relates:

> We do not pay for the renovations of the customers' houses, but we try to motivate them to do it. We show them that it is possible to do, but the residents have to do it themselves. (Int. Andersen, my translation)

Therefore, the map and the catalog are/will be two inscription devices that allow financial flows to be conveyed; through them, the Energy Team can inform their customers about which available subsidies are available, which would otherwise have remained invisible (and unused). In other words, as the utility is itself unable to financially support its customers in carrying out energy renovations, it instead equips them with knowledge about the financial support that is available.

Additionally, the Energy Team mobilized the social ties already developed in Albertslund to motivate renovation projects. Peter D. Andersen relates that they have initiated the making of a citizen 'Energy Group' in a neighborhood, whose task is to disseminate knowledge about energy renovation:

> There is an area that is called 'Røde Vejrmølle Parken' where there are 200 or 300 similar town houses. And out there we have initiated a group of a few pensioners and people from the landowners' association, who sit and talk about how the houses can be energy renovated. (Int. Andersen, my translation)

The Energy Team encouraged a handful of energy enthusiast retirees to create a heat renovation group. They provided the delegation's members with information about the current subsidies and know-how concerning energy renovations that the 'Energy Group' could then disseminate amongst the residents of the neighborhood Røde Vejrmølle Parken.

The uniformity of the urban fabric and the social ties were again assets for the utility; the Energy Team could use the situated standardized buildings in combination with the pre-existing and engaged social ties to find replicable and optimal ways of energy renovating the 200-300 similar houses. They could avoid seeking individual solutions and instead reach up to 300 dwellings in a time-saving manner. The standardized urban fabric, together with the active and cohesive social relations, have allowed the utility to disseminate knowledge efficiently.

7.3.3.2 Making individual heat consumption visible

Tariffs

Traditionally, DH utilities have used a monthly bill to invoice their users' past year consumption. This means that the monthly bill has traditionally not reflected the monthly consumption but has instead been reflecting the average heat consumption of the past 12 months. Concretely, this means that customers pay the same amount of heat in the summer and winter, regardless of what they have actually consumed during the month. The way the invoicing is done, thus, provides the customers very little information about whether or not they have from one month to another consumed more/less heat than usual. Steen Westring, Albertslund Forsyning's director, relates:

> The customers pay the same price over the year, but now that we have the hourly-reading meters, we can send that bill to the customers instead. [The idea] must first be adopted by the user group and then by the municipal council, but we are working on it. It is actually one of the reasons why we decided to set up these hourly-reading meters. (…) Then it may well be that [consumers] react [to their consumption]. (Int. Westring, my translation)

As Steen Westring relates, the Smart Meters have revealed the heat customers' hourly consumption. According to Albertslund Forsyning's employees, a reconfiguration of the bill with this refined data would provide a more accurate representation of individual heat consumption patterns and, in turn, could trigger a modification of the households' heat consumption. In order to have a monthly heat invoice that would reflect the actual monthly consumption instead of reflecting last year's average heat consumption, Albertslund Forsyning is in the process of seeking the approval of the User Group and the city hall to modify the heat invoices from 12 uniform bills to 12 specific bills that reflect the past month's heat consumption. According to Albertslund Forsyning, greater intelligibility of the bill would permit the customers to detect high or low heat consumption, which would allow them to better understand and act upon their heat use.

SmartApp

Albertslund Forsyning also intends to use the data from the Smart Meters in a mobile phone application. The director relates:

> The idea is, and we promised it to our customers, that they will get a SmartApp on their phone, so that they can see the hourly reading of their heat meter at any time. It is not sure that there will be many that will be interested in it, but there will be at least some that will find it exciting. (Int. Westring, my translation)

The idea with the phone application is that the inhabitants will be able to visualize their heat consumption on an hourly basis and, therefore, will have a better overview of their energy consumption. According to Albertslund Forsyning, offering a digital and real-time reading of individual heat consumption would allow the customers to have a better understanding of their heat consumption and, consequently, might motivate them to modify their heat use.

7.3.4. SUMMARY

The utility's project proposal was to develop a 4th generation DH grid, which was received positively by both the city council and the User Group. Considered to be a way of revitalizing the urban composition, the ambitious strategy would permit a reduction in carbon emissions while bringing financial and environmental benefits to the heat customers.

Even though the utility does not have the financial means to carry out energy renovations or produce heat themselves, the Energy Team established two main approaches for reconfiguring the distribution grid. One approach was to extend the utility's agency, while the other was to make heat(s) visible to the customers to motivate them to modify their heat use. In the former, the utility established both physical devices (i.e., smart meters) and contractual ones (i.e., the TAO) to extend and tailor their chain of actions without resorting to the implementation of new technology. In the latter, the utility made both general heat renovations and individual heat consumption visible. In both cases, the utility created new devices making heat(s) intelligible to allow heat customers to reconfigure their usage. Furthermore, the utility intends to use these material devices to make visible what financial support is available and, consequently, enable money flows. These actions render energy reduction 'doable' and attempt to encourage the heat customers to modify their heat consumption as part of an attempt to transform the DH grid from a traditional to a 4th generation grid.

7.4. CONCLUSION

This chapter has explored the attempts made by Albertslund Forsyning to transform its district heating infrastructure from a 'traditional' to a '4th generation' DH grid. Although Transition Studies emphasize the interactions between the niche, regime and landscape, their approach does not seem to capture what energy transitions are made of. This case has shown that energy transitions shall not be reduced to technological displacement from the niche to the regime level (Sovacool and Hess 2017; Roberts and Geels 2019). It shows that the energy transition can also be a pragmatic matter of making a good use of what is 'out there', of dealing with the situatedness (the concerns, the urban fabric, the organizational structure, etc.) and of making the municipality attractive. By focusing on the importance of the local issues and concerns, this inquiry has shown that the 4GDH strategy is as much about renovating the declining urban fabric and making the municipality attractive, as it is about achieving energy transition. In other words, instead of conceptualizing energy transitions as instances of large-scale national technology diffusion, energy transitions might be better witnessed in the practitioners' everyday ordinariness of dealing with the situated messiness.

Moreover, exploring the historical and present conditions under which the municipal utility is trying to achieve a low-carbon transition has revealed the elements from which it finds capacity for action. By focusing on the specificities of the municipality, its organizational characteristics, the socio-urban fabric and past evolution, this account has shown that energy system transitions are bound to the places where they unfold. The issues and means mobilized by Albertslund Forsyning to implement a 4GDH strategy are site specific and are hardly comparable to other 4GDH strategies. This chapter thus provides a more nuanced account of energy system transitions, and moves away from the preconception that energy transitions are objects that are comparable across sites and temporalities (Sovacool 2016; Roberts and Geels 2019).

In addition, this inquiry has exposed the numerous material devices assisting the practitioners in their work towards achieving a low-carbon transition. Some of the devices equip the utility (e.g., the smart meters, the TAO Agreements), while others are meant to equip the customers (e.g., the maps, catalog, tariffs). The latter are enacting a particular form of mundane sustainable engagement and attempt to render the changes ‘doable’. These devices are, nonetheless, based on the assumption that heat customers are rational actors reacting to price signals and information. They are establishing a socio-technical network that constitutes the heat customers in a particular way (as rational agents) and, accordingly, the transition might not occur the way the DH actors expect it (Callon 1998; Jenle and Pallesen 2017).

Whether these efforts will result in a transition from a traditional to a 4^{th} generation DH is, at the time of writing, not known. But if it succeeds, the transition would be the result of a collective effort to reduce heat consumption through the utilization of new material devices, thereby enabling knowledge dissemination and economic flows.

CHAPTER 8. DISCUSSION

This chapter discusses the findings of the empirical chapters but, before doing so, I want to first recall some of the main conclusions of the three case studies. The inquiry about Greater Copenhagen DH system has revealed a plurality of material devices which simultaneously participate in stabilizing and transforming the regional infrastructure. It has highlighted the importance of the (situated) historical developments, the socio-professional associations, and the precarious work of the practitioners in re-assembling their worlds in an evolving ‘environment’. The study of the implementation of the first regional TES has exposed how different material devices have made the world known (and thus, actionable), in particular ways, and how the process of establishing a technology was not predetermined, but rather, ‘emergent by design’ (Garud, Jain, and Tuertscher 2008). Lastly, the study of the attempt by Albertslund Forsyning to assemble a 4GDH grid has shown the work of the practitioners in making heat(s) visible and financial flows to occur through the creation of new material devices.

In what follows, I first discuss my empirical findings in light of some of the key tenets of Transitions Studies. I argue that the relational approach enables one to conceptualize energy system transitions as messy and intertwined processes of change, which may take a plurality of forms. I then argue that, instead of imposing pre-defined categories onto the world, being led by the field leads closer to agency and the unfolding actions, thereby bringing more insights than contemporary energy Transition Studies. Thereafter, I extend an agenda recently developed by Labussière and Nadaï (2018) in that I shift the focus from ‘technological potential’ to be revealed to ‘transitioning potential’ to be assembled.

In the second section, I discuss how technological change should rather be conceptualized as only being the visible outcome of energy system transitions (instead of being the unit of analysis), and that more attention should be paid to the chain of actions unfolding prior to the establishment of a technology.

In the third and fourth sections, I discuss how there may be two types of work enabling energy system transition to occur, namely, what I refer to as being ‘repair’ and ‘inventive’ work, and how these two types of work may be assisted by different kinds of material devices. The sections revisit the empirical findings of the three studied cases and focuses on how the mobilized material devices enable different actions to be performed. These are then followed by a fifth section, which discuss whether these devices may be considered as habilitative or prosthetic, as proposed by Callon (2008).

The sixth and final section discusses how different rationalities and enactments of the current rules and regulations governing DH are leading to controversies and negotiations between different groups of DH actors.

8.1. A RELATIONAL APPROACH TO ENERGY SYSTEM TRANSITIONS

To recall the outline of my argument, the structural ontology (with levels and actor categories) used by transition studies (Schot and Geels 2008) provides a convenient analytical framework which introduces a distance to the field. Transition studies scholars have only offered distant view of energy developments (Garud and Gehman 2012) with the processes of transitioning being strangely absent from their inquiries. Although this distance allows for retrospective analyses of large infrastructural or technological changes from which the causes of change can be inferred, it offers little (or no) insights into the processes involved. Moreover, the attention given to the rise and fall of dominant technologies has led Transition Studies scholars to make claims from the 'outside', in a sort of mechanical and ordered preconception of the world.

The relational approach proposed by Sociology of Translation/Markets scholars enables one to avoid these drawbacks. Inquiring about energy systems as unfolding socio-technical networks allows one to approach the work of transitioning in its nearness and to follow the practitioners, action, and devices.

The following sub-sections discuss the insights that the socio-technical network approach brings in terms of conceptualizing energy system transitions in light of Transition Studies approach and limits. The next section discusses the messiness of DH energy system transition; something which the Transition Studies literature does not address. This is followed by a section that discusses the insights that may be gained from avoiding the use of pre-defined categories and conceptual frameworks (such as 'regimes' and 'incumbency'). The final section discusses the insights that may be gained from moving from 'technological potential' to 'transitioning potential', as proposed by Labussière and Nadaï (2018).

8.1.1. ATTENDING TO THE MESSINESS OF DH ENERGY SYSTEM TRANSITION

Transition studies scholars claim to approach the field as a 'seamless web' and to address the 'dynamic interplay' between the actors, organizations, and technologies (Schot and Geels 2008; Köhler et al. 2019). However, Transition Studies scholars have mainly put technological change at the forefront of these 'seamless webs'. The S-curve representation of technological evolution (and, therefore, energy transitions) seems to have simplified transitioning processes in that it has represented energy transitions as being a matter of technological replacement along which organizational, institutional, and economic changes may occur, instead of analyzing energy transitions as ongoing processes where nothing is predetermined. In other words, despite claiming to approach transitions as 'seamless webs', the technological focus has been pushed into the background of the dynamic relations between the heterogeneous actors partaking in the processes (Garud and Gehman 2012; Labussière and Nadaï 2018).

Taking a relational approach has, however, enabled me to inquire about district heating transitions without determining, beforehand, what types of changes are to be studied or which actions to follow. This has permitted me to reveal the variety of ways in which DH transitions are attempted and accomplished. Further, these transitions are not necessarily technological, as is often assumed by transition studies scholars.

For example, in Chapter 5, the introduction of new market-based policies in the 2000s led to the commercialization of the CHP plants in Greater Copenhagen. This stimulated the creation of new administrative and contractual relations between the producers and heat transmission utilities, which, consequently, transformed the way in which heat was produced and distributed regionally. In other words, an energy transition occurred without any significant change in energy resources or technological infrastructure. Similarly, the analysis of the municipal heat utility, Albertslund Forsyning, in Chapter 7, has demonstrated that energy system transitions to 4GDH can occur without resorting to new production or distribution technologies. In this case, the energy transition is occurring through, among others, the modification of the contractual boundary and through the work of making district heating known and visible to customers in new ways. These kinds of efforts are not captured by the conceptual lenses used by transition studies scholars, which focus on large-scale technological evolution. The analytical scope of their framework does not enable them to 'see' the diversity of ongoing changes that energy transitions entail.

Furthermore, being on the lookout for technological evolutions leads scholars to assume that energy transitions are a matter of large-scale technological innovation and diffusion within regimes (Sovacool et al. 2015; Köhler et al. 2019). However, the analysis of the implementation of the TES (Chapter 6) demonstrates that this is not necessarily the case, and that energy transitions may be more discrete. The TES only represents one of the initiatives of the transmission utilities to reconfigure the DH infrastructure towards a low-carbon future. Far from 'radically' transforming regional DH production and transmission, the transmission utilities are instead trying to adapt the existing infrastructure to new ways of distributing energy by identifying synergies within the components of the existing system. However, the utilities do not intend to replace the system, but rather to reconfigure it. This indicates that energy transition processes may not always occur with long time-lapses between a well-defined starting and end point of affairs, but rather in the everyday work of actors as they attempt to reconfigure elements to one another.

Furthermore, as this type of work is about mobilizing and assembling a multiplicity of heterogeneous actors, energy system transitions are inevitably uncertain. This is most clearly illustrated by the five-year implementation process of the TES. In this instance, although the technology was not new, questions regarding economic, technological and organizational elements introduced uncertainty regarding the feasibility of the project. The lack of stabilized knowledge impeded the stakeholders in knowing the technology and reaching an agreement, and forced them to mobilize a multiplicity of material devices to calculate and grasp their worlds. In other words, the in-depth analysis of the implementation of the first TES in Greater Copenhagen has demonstrated that energy system transitions also involve coming to grips with the situation and trying to clarify, negotiate and stabilize vexing issues so as to 'make things work'. It is about dealing with the messiness of the world – making it known and stable – rather than just being a matter of technology maturity and strategic management as argued by Transition Studies scholars (Schot and Geels 2008; Köhler et al. 2019).

Altogether, these three empirical close-ups show that energy system transitions are more than windows of opportunities and technological replacement (Schot and Geels 2008). Rather, energy system transitions appear to reside in the continuous and mundane work of the actors in dealing with uncertainties (about expectations, projections, calculations, etc.) and in re-configuring the elements (the technologies, actors, devices, etc.) of their socio-technical networks.

8.1.2. BEYOND CATEGORIES

Transition studies scholars assert that change emerges from the 'dynamic interactions' between the salient conceptual distinctions of the niche, regime, and landscape levels (Schot and Geels 2008). These categories have been criticized for not clearly designating who or what they encompass and for black-boxing actors as consciously maneuvering against/for change (Birch 2016; Quitzau et al. 2013).

In response to this criticism, Geels recently added that dynamic interactions may also occur between different niches, and he has refined the dichotomous qualification of challengers and incumbents by claiming that both may bring about change (Geels and Johnson 2018; Turnheim and Geels 2019; Geels 2019). Nonetheless, these scholars still approach the field with a structuralist and normative view of action; they consider actions as resulting from tensions between pre-defined levels, technologies as being path-dependent, and actors as belonging to established categories. When taken together, this constrains them in terms of approaching action and agency as precarious achievements and situated outcomes (Garud and Gehman 2012).

I want to argue that, despite the convenience that having pre-defined analytical categories may provide, they nonetheless restrain Transitions Studies scholars in their attempts to conceptualize energy transitions because the categories direct attention to particular 'things', which may exclude beforehand the formulation and investigation of the concerns and problems occurring in the field. Hence, rather than continuing to refine and more precisely delineate what constitutes niches, regimes, and landscapes, and applying these to the 'outside world', I suggest letting the 'outside world' lead researchers to the concerns and problems. The Sociology of Translation invites one to do so. The methodological tenet of 'follow the actors' invites one to enter the worlds of practitioners and see how they assemble their worlds, thereby enabling processes to be made analytically and empirically visible.

Letting the actors in the field express what matters instead of the other way around provides, I argue, a more sensitive account of the agency and details of energy transitions. Rather than imposing pre-defined views on what energy system transitions and their barriers are, this allows one to follow transition processes *in the making.* Such an ontological turn to the energy transition field demands that one attend to the messiness and precariousness of the unfolding actions. It calls for a change in analytical focus from distant, retrospective, and longitudinal to near and open-ended (Shove and Walker 2007; Birch 2016; Labussière and Nadaï 2018).

Following the actors' definitions of what matters also answers the question as to who has the legitimacy to qualify and categorize an element, or an actor, into one category or the other. Instead of having academics qualify a power utility as being a *de facto* powerful actor, it is the power utility (and the other field actors) who categorize its agency. Consequently, qualifying whether the power utility is a powerful actor is the outcome of the (situated socio-technical) network configuration.

Furthermore, the socio-technical network approach permits one to address the 'seamless web' between technology and society as one relational assemblage instead of as layered levels. Considering energy transition as "*an effect generated by heterogeneous means*" (Law 1992, 382) directs attention to the technologies, people, pipes, buildings, and material devices involved in the making of energy transitions as well as the tensions and interactions taking place within the network. Instead of considering these as being bidirectional or taking place between pre-defined levels (e.g., regime-to-niche, landscape-to-regime), they can be considered as being multidirectional, complex and precarious.

By bringing the complexity and messiness of the "outside world" into the analyses, this approach facilitates another type of account of energy transitions than that provided in the Transition Studies literature. It enables one to approach actions and agencies in their nearness and explains why things do not go as planned or modelled. This can enrich the understanding of the ongoing tensions and interactions in energy transitions.

In other words, the relational approach calls for being less "object-oriented" and more "problem-oriented" (Marres 2007). It implies that one abandon the convenience of solving well-defined academic problems and instead let the field "*determine what is problematic and what is not*" (Callon 1980). This point is developed further in the following.

8.1.3. TRANSITIONING POTENTIAL

Transition studies scholars commonly adopt the evolutionary economics view that technologies have a ‘potential’ to be revealed through a mix of better management, better-suited policies, and business models (Kemp 1994; Geels 2002; Jacobsson and Bergek 2004). According to them, once the potential of a technology has been revealed, the technology can diffuse and become predominant in an established regime, thereby leading to a ‘sustainable’ energy transition. In such a structuralist approach, potential is an intrinsic technological quality that may, or may not, be unveiled for achieving desired energy transitions.

Labussière and Nadaï (2014, 2018) propose approaching the topic of technological potential from another perspective. Instead of assuming that the potential resides in the technologies, they suggest that the potential does not reside in the technology/energy resources themselves or solely in the (situated) network but is instead a result of the articulation of both. The scholars argue that such an approach can account for the complexities and specificities of each transition. They explain:

> The ‘transition potential’, then, can be defined as the potential of a situation, or process, to jointly assemble and redefine its public, its objects, and the political principles that hold them together, in a manner that acknowledges all the interferences at work and allows for the necessary transactions to take place (Labussière and Nadaï 2018, 333).

According to Labussière and Nadaï (2018), the success of energy transitions thus resides in the association between specific technologies (or resources) and the socio-technical networks within which they exist. They argue that inquiring about ‘transitioning potential’ allows one to diverge from the simple notion of ‘technological potential’ and to conduct a more nuanced study of energy system transitions by allowing one to observe how potentials are framed/qualified (Labussière and Nadaï 2014, 2018).

As each DH system is different, inquiring about ‘transitioning potential’ instead of ‘technological potential’ appears particularly relevant for the study of DH transitions. DH systems are highly dependent on the specific building stock, the age and layout of the pipes, the energy production mix, etc. Thus, they are not inherently ‘sustainable’ or efficient’ but are so as the outcome of their situated configuration.

For example, Albertslund Forsyning’s energy transition could be interpreted as the the diffusion of 4GDH technologies. However, following Labussière and Nadaï’s (2014, 2018) argument, Albertslund Forsyning’s transitioning potential rather resides in the utility’s relations with the customers, facilitated by the relatively small size of the municipality, a long history of socio-democratic rule and a pioneering mindset amongst municipal politicians, administrators and citizens. In Høje-Taastrup Forsyning, the neighboring DH utility, the transitioning potential rather seemed to reside in the integration of local energy resources and in mobilizing the available municipal space for digging a 70.000m3 TES. Similarly, in Greater Copenhagen, the sustainable transitioning potential resulted from the conversion of the CHP plants from coal to biomass and the (momentarily) successful framing of the resource as being carbon neutral. In this case, it seems quite clear that the gradual collapse of the resource's framing is threatening the sustainable potential of the regional DH infrastructure, even though the materiality of biomass has not changed. Labussière and Nadaï (2018) argue:

> The originality of this [socio-material] approach is to propose a shift from energy materiality in general (...) to a specification of energy materiality within its geographical environment (...), and then to propose an analysis of the interferences and political issues related to these practices of calculation, navigation and dis/connection (Labussière and Nadaï 2018, 261).

In this way, biomass can be approached as an energy resource whose transitioning potential depends on the site where it is being exploited. The resource is not *de facto* 'sustainable' or 'unsustainable'. Rather, its potential of being 'sustainable' is a network effect. In Greater Copenhagen, it appears as if the volume and scale at which biomass is currently being used has become unsustainable, and, consequently, its transitioning potential has gone awry (Eriksen 2021). The use of biomass was encouraged by the Danish Government to reduce carbon emissions and was introduced in the 2010s in Greater Copenhagen as an alternative to coal. The intention was to change the status quo of the energy production and engender sustainable energy production. At the time, biomass in the form of straw was framed as an abundant surplus local product, and its transitioning potential appeared to be realized as an increasing number of CHP plants began to substitute coal in favor of biomass. Today, the exploitation of biomass in Greater Copenhagen and Denmark as a whole has grown out of proportion, and the use of the local surplus product has given way to imports of industrial volumes of foreign wood pellets, hereby hampering the transitioning potential of the resource and Denmark's green reputation as more than 20% of the country's 'renewable energy' is biomass. This example clearly illustrates that the transitioning potential is not intrinsic to just the material resource or technology being used, but is instead intertwined with the material resource in a situated socio-technical network (Labussière and Nadaï 2018; Karnøe, Iuel-Stissing, and Georg, n.d.).

In summary, focusing on transition potential rather than technological potential directs attention away from normative categorizations of resources/technologies as having intrinsic proprieties that define their sustainability. Furthermore, it emphasizes how the qualities of resources/technologies are 'produced' through negotiations and alignments in the socio-technical networks in which they exist.

8.2. SITUATIONS OF PROBLEMATIZATION

Transition Studies analyses are object-oriented (e.g., focusing on large-scale technological diffusion), whereas those contained in this thesis are process-oriented (e.g., focusing on the processes of transitioning). Concretely, the analyses in Chapters 5, 6 and 7 did not start with the end of the transitioning processes or a point when the new technologies had already been established. Instead, I followed the formation of the issues and the actions taken to solve them. Considering energy system transition as a network effect provides a new approach to the phenomenon, which helps to reshape the academic agenda.

This is also in keeping with Callon's (1980) call to attend to situations of "*problematization*" in the field. According to him, inquiring about how problems impose themselves among practitioners is fundamental in what is made known, what actions can be undertaken, and what effects this can lead to. He explains '*problematization'* in the following:

> The problematization carves out a territory which then cuts off from the outside, forming a close domain with its own coherence and logic. (...) Next, a second frontier is traced between what is intangible, taken for granted, and what is problematized or unknown. In other words, in order to formulate problems and mark off zones of ignorance, protagonists necessarily take as their basic concepts, systems of interpretation and reasoning which are then given the force of certainties and thus totally escape suspicion. (...) Problematization must of necessity rest on elements of reality (concepts, proposals, matchings up, results...) which are considered irrefutable and firmly established (Callon 1980, 206).

According to Callon (1980), protagonists (or practitioners) draw lines between what is known and certain, and what is unknown and to be calculated. Problematization is, thus, an array of mechanisms through which an issue or situation is framed, acted upon, thereby leading to particular results. I want to propose that in the three studied instances, energy transitions form a chain from one problematic situation to another, as illustrated in Figure 14, below.

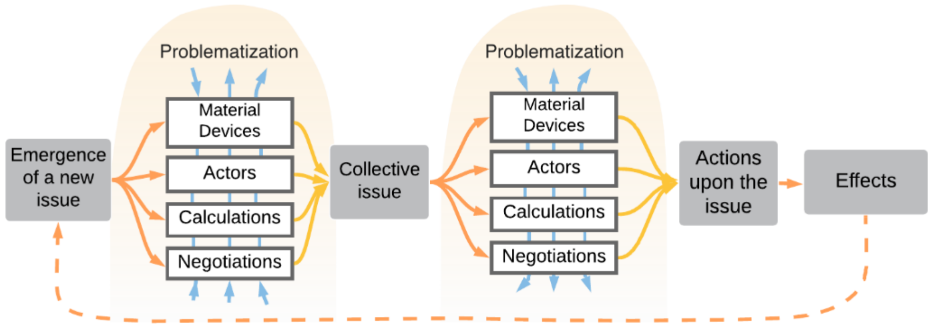

Figure 14: The precarious translation of issues into effects

In each studied case, a new issue emerged, provoking a phase of *problematization* (i.e., the mobilization of different actors, calculations, material devices and negotiations) which, in turn, transformed the matter into a '*collective concern'* (C. Frankel, Ossandón, and Pallesen 2019) or 'collective issue', that is, an issue shared by many in the field. Once the issue has been translated into a joint matter, another problematization situation then starts, in which more actors, material devices, calculations and negotiations are mobilized. At the end of the problematization situation, what is certain, uncertain, and to be acted upon, is defined, thereby leading to specific outcomes.

For example, the oil crisis in 1973 was an issue which provoked a phase of problematization; different actors mobilized their tools and knowledge, defining what was known and what was uncertain. This translated the issue into a collective issue for the Greater Copenhagen DH practitioners, namely, the implementation of the regional DH transmission grid and its ownership model. A plurality of actors was, thus, enrolled in a new phase of problematization, directed to framing and making the issue manageable. This problematization situation led to a municipal disagreement between the Western and Eastern municipalities, which, through negotiations, actions, and the use of devices to make the world known in particular ways, framed the action to be taken on the issue, namely, to implement two transmission utilities instead of one. This led to the outcome of having two transmission companies with their own customers, organizational structures and economic means. This effect, taking place in a continuously evolving environment, may provoke the emergence of new concerns in the future. For example, having two transmission utilities instead of one is currently part of considerations as to how to integrate local heat sources.

Similarly, the TES is an outcome of an entire series of issues, problematization situations and actions. The DH practitioners' issues were to integrate more fluctuating energy and to reduce the use of peak load productions. This led VEKS and HTF to a situation of problematization in which they calculated, negotiated and mobilized devices in trying to make a new technology known and actionable. The problematization turned the issue into a collective one: it calculated that the technology had to be established as a regional piece of infrastructure (instead of a municipal one) and, thus, that all the DH actors were to be a part of it. This, consequently, provoked a new problematization where all the producers and the heat utilities were to mobilize their own devices and calculations. From there on, different phases of problematization followed one another, defining what was uncertain, problematic, known, and thus, actionable. At the end of the 5-year process, agreement about which actions should be taken was reached, which resulted in the establishment of the first regional TES. Also, it is likely that the TES will, in the future, partake in the emergence of new issues for the regional actors (such as the implementation of other TES).

In Albertslund, the issues are a hodgepodge of environmental concerns, declining urban fabric and pioneering and socio-democratic ideals. These issues have led to a specific low-carbon future problematization for Albertslund Forsyning, which, after calculating different alternatives, established the 4GDH strategy. This, in turn, involved the municipal DH practitioners and customers in the transition of the infrastructure in new ways: the heat customers are to prepare their households for a 60°C supply temperature, and the heat practitioners are to create new devices that are more efficient and which can incentivize the customers in changing their consumption. Therefore, the issue was turned into a collective matter. The outcomes of the actions taken on the collective issue are, as of today, not fully known.

In this understanding of energy system transitions, technological changes are only the effects of the chains of issues, problematizations, and negotiations. Depending upon the instance, there may be a need for more or fewer iterations of the mobilization of material devices, actors, and calculations. Additionally, even though the illustration makes it look like a simple and straightforward chain of events, it must be noted that each of the elements represented interact with a whole array of other elements in an unstable environment. These interwoven events are unfolding against a backdrop of uncertainties, which are related to the calculations, projections of the future and the unstable environment in which they occur. Accordingly, the chain of events and their effects remain precarious, undetermined, and emergent. The outcomes can never fully be predicted.

Such an open conceptualization of energy transition enables one to address the messiness of energy system transitions in the making and directs attention to the process of transitioning rather than the technological object of the transition (yet without denying it). It also sheds light on the specific (situated) issues and framing that unfold in each instance, while leaving their origins and effects open instead of imposing levels of interactions between the elements.

8.3. TRANSITION WORK AND MATERIAL DEVICES

My inquiry has explored the work of the practitioners in their attempts to assemble 'energy system transitions'. It has followed their uncertainties, practices of calculations, material devices, and ways of griping hold of their situated socio-technical networks.

The practitioners have a dual task at hand; firstly, they must maintain the security of supply, and secondly, they have the ambition to assemble a transition. In the following two subsections, I elaborate on the effects of what may be considered two different types of transition work, namely, maintenance (or repair) work, and 'inventive' work, i.e., the work of assembling alternatives.

8.3.1. MAINTENANCE (OR REPAIR) WORK

The work of repairing or maintaining continuity may refer to the set of routines, procedures, discourses, and devices that are mobilized by the different actors composing the network in order to ensure that the socio-technical system keeps operating as it has done previously. In the sites studied, repair work refers to the daily operations of producing/distributing heat, identifying pipe leaks, investing in new pipes, sending bills to the customers, etc. Existing routines, knowledge, procedures, and devices used offer a 'good' response to some of the practitioners' daily issues that they have to deal with to keep the system running. All of these things facilitate the practitioners' work of maintaining the system.

Albeit necessary, repair work may limit the resilience of socio-technical networks. For example, in the aftermath of the liberalization of the power sector, the work of maintaining the continuity of the centralized heat production and transmission necessitated the creation of a whole set of material devices (heat contracts), organizations (Varmelast), procedures, and routines (daily heat load dispatch scheduling). Today these devices, procedures, and routines arranged to maintain a heat load dispatch centralized around a few large CHP producers seem to render difficult the integration of decentralized heat sources, which is increasingly being recognized as a significant part of the low-carbon DH future. Integrating the smaller and decentralized productions does not 'fit' into the routine, thereby hindering their integration. To this end, maintaining the continuity of the regional heat load dispatch operation seems today to hinder the transition of the regional infrastructure.

This is in keeping with Geels's views of which actors bring about change (Schot and Geels 2008; McMeekin, Geels, and Hodson 2019; Roberts and Geels 2019). According to Geels and Transition Scholars at large, established actors, such as DH utilities, are powerful incumbents who benefit from increasing returns and who limit change to protect their vested interests and, thus, only newcomers can promote radical alternatives. However, what the relational approach can capture and what the structuralist ontology of MLP cannot, is that this ‘repair’ is not the result of incumbent actors’ efforts to limit change due to a fear of losing their agency. Rather, it is the work of actors griping hold of their world and maintaining a secure heat provision despite the changes in their unstable environment. Moreover, despite limiting the resilience of the socio-technical network, repair work does not exclude simultaneously attempting to assemble energy transitions. As developed in the following section, the actors do not engage in *either* repair *or* ‘inventive’ work, but rather in repair *and* ‘inventive’ work.

8.3.2. ‘INVENTIVE’ WORK

I use ‘inventive’ work to refer to the work of coordinating actions towards uncertain alternatives. It may refer to the introduction of new technologies, which can be considered as means of moving to a low carbon energy system, to the implementation of new material devices, or to the establishment of new forums for discussion.

For example, the HPCs are the forums where the regional heat producers, municipalities and heat municipalities meet to discuss and negotiate how the regional infrastructure is to transition towards a low-carbon future. Although they have to continue to ensure the heat provision, which (through routines and associated practices and devices) may limit the transition, there is still room for assembling ‘inventive’ work. For example, the HPC forum has (after a long chain of uncertainties and calculations) led to the establishment of the first regional TES, despite being a decentralized heat source which did not ‘fit’ with Varmelast (and the related procedures) organization. However, through calculations, efforts and negotiations, the practitioners did manage to make it ‘fit’ despite the centralization of the heat provision around the five large-scale heat production units.

Similarly, it can be argued that Albertslund Forsyning is simultaneously engaged in repair and in ‘inventive’ work when trying to transform the municipal DH grid from a traditional to a 4th Generation DH. In this case, the heat utility continues to ensure the security of supply *and* mobilizes new discourses, devices, economic flows, etc., to transition the municipal infrastructure towards a 4GDH grid. Even if the (situated) elements (the built urban fabric, the pipe layout, the low-financial means) seem, at a first glance, to limit the transition, the repair work of identifying leaks, sending bills to customers, and related routines still leaves room for assembling ‘inventive’ work which, eventually, may lead to a transition.

In other words, it appears that there is not, on one hand, repair work performed by incumbents and only ensuring the heat provision and limiting alternatives, and on the other, ‘inventive’ work performed by new entrants and promoting alternatives (Roberts and Geels 2019). Rather, the practitioners are in tension between the two; they are carrying out maintenance work while, at the same time, assembling ‘inventive’ work. This dual work may, eventually, realize transitioning potential (Jensen et al. 2015; Labussière and Nadaï 2018).

8.4. RELATIONSHIP BETWEEN MATERIAL DEVICES AND TYPES OF WORK

In this section, I discuss how the two types of work identified in the above section are assisted by different material devices. The sub-sections provide a succinct discussion of the three empirical chapters focusing on the actions that these devices enable.

8.4.1. GREATER COPENHAGEN, DYNAMICS OF STABILIZATION AND TRANSITION

The analysis of Greater Copenhagen (Chapter 5) has revealed a plurality of material devices. On the one hand, there are the devices that were created in the aftermath of the liberalization of the electricity sector (Varmelast, heat contracts, spreadsheets) and those that were created to steer and coordinate future actions (HPCs). I propose that these two types of devices are indicative of the two types of work identified in section 8.3, namely, repair and inventive work.

The devices associated with repair work are used on a daily basis: they feed into one another and they ensure the daily heat provision as a result of their combination. Concretely, the heat contracts cannot fulfill their function (the heat trades) without Varmelast dispatching the heat load (based on the heat costs) or without the spreadsheets (ensuring that planned and actual dispatch match). These devices are highly coordinated and combined; they facilitate the practitioners’ maintenance (or repair) work. If one of the devices stopped operating, heat provision would fail.

The devices associated with inventive work (the HPCs) are used over a long time span and appear to replace (and feed into) one another. HPC 1 was the first projection of the future DH infrastructure. It was based on the configuration of the infrastructure at that time and on energy outlooks provided by other actors (e.g., the DEA). Its creation led to different actions in the metropolitan area (meetings, coordinated strategies, calculations, etc.), which have gradually contributed to transforming the socio-technical network. Consequently, the configuration of the infrastructure changed, and the HPC 1 was no longer relevant. Therefore, a new projection of the future could be made (HPC 2) based upon the HPC 1, thereby enabling the calibration of former expectations to the occurred developments. Therefore, HPC 2 replaced HPC 1, which became obsolete. Subsequently, HPC 2 led to a new range of actions, meetings and calculations, thereby modifying the socio-technical network, and HPC 2 gradually became obsolete. HPC 3 recalculated and projected a future according to the evolution of the socio-technical network and the new energy outlooks, thus replacing HPC 2. These devices enable the practitioners to perform inventive work by providing them with a calibrated basis for calculations, taking into consideration the current configuration of the system and future outlooks.

Furthermore, the two different sets of devices, despite enabling different kinds of work, feed into one another. Concretely, the newest HPC takes the present operation of the daily heat load dispatch into account when projecting the future. For example, HPC 3 takes the current subsidies, taxes, and socio-economic costs into account as well as the current DH distribution and operation when calculating the 2035 outlook. HPC 3 calculates the future according to the various current production units and the organization of the regional heat provision (CTR, HOFOR, and VEKS 2014, 18). Similarly, the daily heat-load dispatch also interacts with the HPCs. For example, in the HPC 3, it says that "*a more decentralized production structure with more heat-producing units will place new demands on the overall network and the operation*" (ibid., 14). Consequently, Varmelast has initiated a working group to find out how to keep operating the regional heat distribution with more decentralized heat production units. Accordingly, the material devices that facilitate the repair and inventive work appear to interact and co-evolve. Figure 15 illustrates some of the interactions between the above-mentioned material devices, although it is only a flat representation that cannot capture the many ways in which these devices 'feed into' each other.

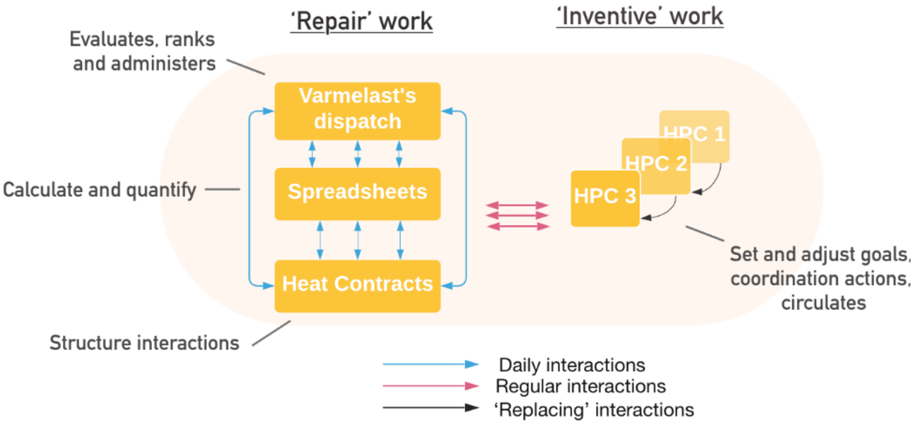

Figure 15: Material devices dynamics in Greater Copenhagen

The figure illustrates the high intensity of interactions among the daily heat planning devices used in the repair work, and regular interactions with the future making devices used in the 'inventive' work. Both sets of devices are co-evolving and feeding into one another. Therefore, when combined, the material devices seem to both stabilize and to transition the Greater Copenhagen DH system.

The work of assembling (today) the DH system transition (in the future) depends on the combination of the material devices at hand; the devices provide the actors with the necessary information, thereby assisting them in maintaining the daily heat provision while calibrating action towards a particular future. The interaction between the material devices enables the actors to simultaneously engage in repair work (with the daily use of Varmelast dispatch, the spreadsheets and heat contracts) while, at the same time, leaving enough room to perform inventive work (with the HPC circulating and coordinating actions for the future).

8.4.2. TES, OPENING AND CLOSING DOWN UNCERTAINTIES

In the implementation of the TES, the mobilized devices appear to support ‘inventive’ work by ‘bringing into being” a new infrastructural unit. In this case, it appears that the succession of material devices solved some issues while simultaneously creating new ones.

The idea of establishing TES first emerged from the HPC 3, which calculated that the capacity of the regional TES needed to be increased by a factor of ten to integrate a greater proportion of fluctuating energy sources. This led VEKS and HTF to calculate and frame the implementation of the first TES, which simultaneously raised questions as to how it was to be operated. The Ea EnergiAnalyse reports then established that the TES could only be operated as a short-term storage and shared infrastructure. This material device, thus, provided sufficient information to stabilize the concerns as to whether the TES was worthwhile. However, at the same time, it created uncertainties in terms of how the TES investments were to be split. In turn, the five producers and the heat utilities mobilized their own material devices (e.g., business models, modelling software), which created some information as to the actors’ respective profits. However, due to a lack of information regarding the technical operation of the technological unit, the future energy outlook and the respective earnings, uncertainties were still present. In that measure, the actors created a focus group, the aim of which was to deal with the remaining uncertainties. Figure 16, below, illustrates this alternation of stabilized information and uncertainties (or what may be considered as instances of framing and overflows (Callon 1998)) and the roles of the material devices within it.

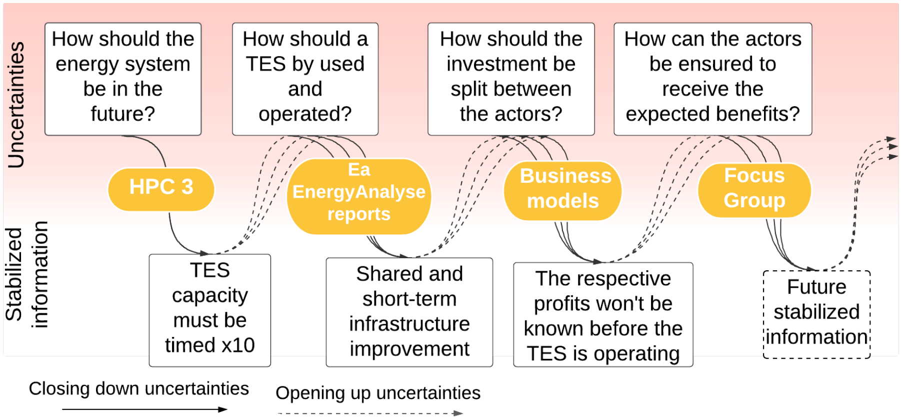

Figure 16: Material devices dynamics in the implementation of the first regional TES in Greater Copenhagen

It appears that each device reduced some uncertainties while simultaneously creating new ones. As a result of the accumulative calculative process, the uncertainties were made manageable, and the TES became stabilized enough to be brought into being.

8.4.3. ALBERTSLUND FORSYNING, DISTRIBUTING ACTIONS AND ENROLLING CUSTOMERS

Lastly, the study of Albertslund Forsyning reveals another type of material device dynamic and work. In this case, the practitioners are simultaneously maintaining the heat distribution while assembling a transition towards 4GDH through inventive work. Unlike in the two previous cases, the devices used are 'stand-alone'; they distribute specific actions and rely only to a limited extent on other devices for the action to be performed. For example, the map makes the already completed and the planned/future renovations of Albertslund's building stock visible to the customers, whereas the catalogues make technical and economic information about heat renovations visible to them. However, removing the map would not prevent the catalogue from rendering the information visible, and, similarly, removing the catalogue would not prevent the map from fulfilling its function.

Furthermore, both the SmartApp and the motivation tariffs make heat consumption visible to the customers: the former by providing a digital visualization of the time-based heat consumption, and the latter by establishing a monetary association between heat consumed and the heat bill. However, the two devices do not rely on one another to fulfil their purpose, the SmartApp does not need the heat bill to enable the visualization, and vice-versa, the heat bill does not need the SmartApp to make the association. And once more, the Smart Meters and the TAO agreements enable Albertslund Forsyning to optimize the municipal DH grid, but they do so independent of one another.

The devices are complementary in the sense that, together, they may enable the utility to assemble the municipal energy transition. Nonetheless, the withdrawal of one of these devices would not prevent the others from assisting the practitioners in their move to 4GDH. Figure 17, below, illustrates the material devices distributed by Albertslund Forsyning.

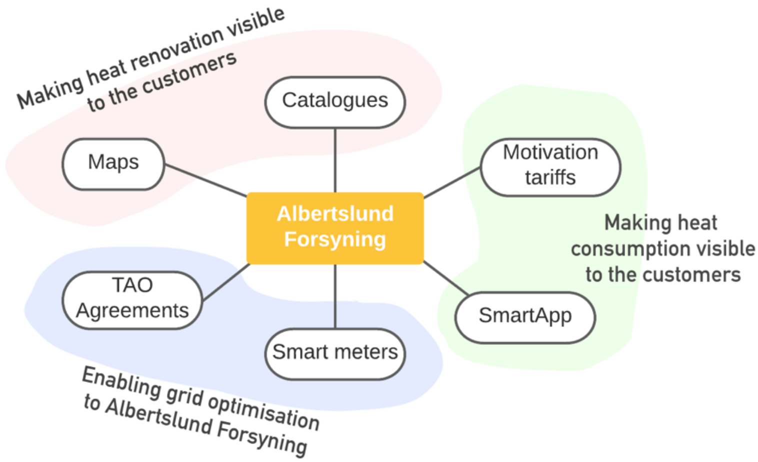

Figure 17: The dynamics of material devices in Albertslund Forsyning

In this municipal case, the devices are neither interwoven nor used succinctly, but are rather distributed and complementary as a result of the task at hand. But as the devices that make heat(s) visible are based on the assumption that customers are rational actors that will react to price signals and information, there is the possibility that it will not lead to the expected outcomes. There is a risk that the customers will not play the role that the utility has assigned them to perform, and, consequently, a risk that the devices will not facilitate the 4GDH grid transition as expected. In other words, the outcome of the practitioners' efforts in assembling the municipal transition remains unpredictable and precarious.

8.4.4. THREE ARTICULATIONS OF DEVICES REFLECTING TWO TYPES OF WORK

The three studied instances have revealed that the practitioners are simultaneously engaging in repair and 'inventive' work, and that both types of work are assisted by a multiplicity of material devices. These material devices are diverse in their shape and in terms of what they enable. They make different objects and situations in transitioning processes visible, knowable, and actionable. They allow new objects to be brought into being, stabilize information, and identify uncertainties. Consequently, they assist the practitioners in both stabilizing their world and facilitating their transition.

Material devices may be combined and rely on one another to perform the task at hand, and they may also be stand-alone. In any case, the outcomes of the material devices remain precarious and unpredictable. The devices may reinforce the obduracy of the socio-technical network in which they exist, but they may also offer new capacities for action. They are mobilized in an environment which is itself moving and unstable, which always leads to unexpected issues.

Although this limited sample of articulations of material devices and types of work does not allow one to make any generalizations about what it is that devices do, as it is always a situated network effect, it does prompt new thoughts on how we might think about material devices. For example, it reveals two distinct ways of working namely, *habilitation* and *prosthesis* (Callon 2008), which are discussed in the following section.

8.5. HABILITATION AND PROSTHESIS DEVICES

According to the relational socio-technical perspective, the individual actor and the network are mutually constitutive (Callon 1986b; Muniesa 2015). Therefore, the inability to take a decision (stemming from a lack of 'calculativeness') may either come from the individual or from the network within which this individual is situated. Callon (2008) argued there are two ways of repairing this 'calculativeness', namely, through *habilitation* or *prosthesis*. The prosthesis approach aims to extend the actors' agency by providing them with new (prosthetic) material devices, whereas the habilitation approach aims to transform the actors' environment to reconfigure their agency with (habilitative) devices. Callon (2008) explains:

> Prosthesis, irrespective of what they are, equip individuals in such a way as to give them a capacity to act and move in society. This capacity for action (which is, as any action, distributed) imposes a very specific model in which the individual is autonomous to the precise extent that, in a disciplined way, she follows the course of action allowed by the prostheses and inscribed in them (Akrich 1992). Habilitation is a quite different approach. It is based on the idea that there is no reason to act exclusively on handicapped persons to reduce the maladjustments they are suffering from. Instead of focusing on the extension of the individual by successive articulations and integrations of prostheses, as in the case of the prosthetic adjustment, habilitation is also directed at the individual, but starting from the outside environment. As it goes along, it shapes devices, procedures and forms of organization, aiming for the inclusion of the handicapped person in an interactive diagram (Callon 2008, 44).

The two approaches, thus, consider the origin of the maladjustment as being network effects coming from two opposite ends. The prosthesis approach refers to a situation where the source of the weakness belongs to the individual, whereas the habilitation approach refers to a situation where the weakness belongs to the network.

It could be argued that the two approaches are tied to the two types of work identified earlier in this section, namely, repair and inventive work. Repairing is tied to the use of prosthetic devices; they are the ordinary tools that equip and articulate the practitioners' calculativeness in their mundane work. These devices are 'in' the network of things. They can refer to the business models, the modelling software, or the energy outlooks that equip the practitioners. For example, the combination of Varmelast heat load dispatch mechanisms, the heat contracts and the spreadsheets articulate the actors and the necessary information, thereby fixing their ability to act in achieving the daily heat load dispatch.

On the other hand, inventive work ties the use of habilitative devices; new tools, forms of organization, procedures and mechanisms are needed to include more actors in the socio-technical network and enable them to participate in the energy transition process. For example, the maps, catalogues, motivation tariffs, TAO Agreements, etc., used in Albertslund Forsyning, are 'out there', trying to enroll the customers in new ways of enacting their heat practices. Similarly, the business model created to implement the first regional TES is a habilitative device, purposefully including more actors through a new organizational form and providing them with a common source of 'calculativeness'.

It can also be said that these two approaches have a temporal dimension; a material device that was once habilitative may become prosthetic as a network effect. For example, it can be argued that, in the aftermath of the liberalization of the electricity sector, the practitioners had to engage in 'inventive' work to re-stabilize their environment. They resorted to new habilitative devices such as Varmelast, the spreadsheets and the heat contracts, which have restored the actors' calculativeness by including the regional heat producers and heat utilities in a new and shared form of organization, thereby reshaping their environment. However, as time has passed, these devices have become 'business as usual' for the practitioners – the regional DH provision routine and actors' positions relative to one another have now become well established and taken for granted. In other words, as a gradual network effect, inventive work turned into daily repair work, and the habilitative devices turned into prosthetic devices articulating the mundane daily heat provision.

Similarly, the shared business model established for implementing the first regional TES once had a habilitative role: it was 'out there', reshaping the procedures and form of organization with the aim of including all the producers in the project. Now that the device has been made, it is gradually becoming an integrated part of the socio-technical network, turning from being 'out there' to being 'in there', from being a new and inclusive device to being an ordinary prothesis to which the heat practitioners will resort in shared investment situations.

Similarly, the maps, catalogues, TAO Agreements, and other habilitative devices aiming to enroll Albertslund's heat customers (considered as being handicapped in terms of their heat consumption 'calculativeness') in the socio-technical network, may, over time, become articulated protheses to which the customers will resort on a regular basis. They may, gradually, move from being habilitative devices that support inventive work to being prosthesis devices that support repair work and to being part of the common heat procedure.

The point is that something that one day is considered 'inventive' work assisted by habilitative devices, may over time come to be considered as 'repair' work assisted by prosthesis devices. Whether a device becomes one or the other is a network effect and should, therefore, not be taken for granted.

8.6. DIFFERENT RATIONALITIES AND ENACTMENTS OF THE DH REGULATIONS.

In the course of conducting the different studies, it seems that the actors were dealing with a long-lasting controversy. Although this controversy was not the focus of my investigation, I still note its importance and would like to seize the opportunity to address it in this section. The nature of what follows is, therefore, slightly different than in the previous sections; instead of discussing insights that have been discussed in Chapters 5, 6 and 7, this section supplements the analytical chapters with additional empirical elements. This section discusses the different rationalities that manifest themselves in the Danish district heating socio-technical networks. It is an attempt to define the basis for the different groups of actors' calculations (and, therefore, decisions) in their effort to impose their own problematization of situations.

To recall the beginning of DH in Denmark, the initial infrastructure developments were carried out in the wake of the 1973 oil crisis. The national policy concern was to find a solution that would ensure the security of the energy supply at a low cost for society. Following (and co-evolving with) the initial infrastructure developments, the governance structure fell into place, making DH a visible technology with its own set of rules, market, and organizational structure (Karnøe and Jensen 2018). DH was, thereby, turned into a coherent governance object that could rapidly expand at a low cost for society (Karnøe and Jensen 2018). As of today, more than 40 years later, DH actors still need to comply with these regulatory devices when initiating heat supply development.

The ways in which these regulatory devices are enacted is, however, open to interpretation, which leads to different representations of the DH sector. Concretely, it appears that some of the DH practitioners see the rules as limiting their actions and efficiency. On the one hand, some of the interviewees mentioned for instance the difficulty they experienced in terms of getting rid of old steam infrastructure in favor of district heating pipes because the projects did not have a positive socio-economic benefit due to the infrastructural costs associated with DH and the unaccounted for carbon emissions from gas and oil. Some practitioners also said that they were limited regarding their strategies because the socio-economic calculations favored imported biomass (about which practitioners had, and still have, some concerns regarding its actual sustainability (Karnøe and Jensen 2018)) to alternatives such as heat pumps, geothermal, and local industrial heat (Øyen 2018; Mortensen 2019; *dr.dk* 2020).

These regulations stem from a rationality of security of supply and are still in place today, although the main DH infrastructure has been established and the concern about security of supply has vanished. The regulations are thus interpreted by many DH practitioners as being obsolete and to no longer correspond to the situation at hand. Consequently, many DH practitioners are asking for the regulations to be 'modernized' (Munksgaard 2018; K. Mortensen 2019; Lotte 2019). For example, Anders Jespersen, consultant at the Danish District Heating Association (DDHA), relates:

> The interplay between the socio-economic and the company financial calculations is a constant challenge. For several years, the planned investments in the most economical energy sources, such as local biomass, heat pumps and solar, have been more or less slowed down by the socio-economic calculations, as it is difficult to achieve a positive financial result with these green projects" (Anders Jespersen, Dansk Fjernvarme (2017), author's translation).

It seems that the DH practitioners do not think that the rationality upon which the rules and procedures are based as are in line with the tasks at hand, namely, renovating the DH infrastructure (e.g., removing old steam pipes) and assembling a green transition.

On the other hand, it appears that the national authorities interpret the lack of efficiency in the DH sector as being the result of a lack of market competition. The authorities claim that the present regulations do not motivate the DH utilities to be economically efficient. Their assumption is, therefore, that if competition in the sector were higher, inefficient utilities would lose and be replaced by more efficient alternatives, which in turn would drive the heat prices down (Munksgaard 2018; O. Andersen 2020a; The Danish Utility Regulator 2020). In 2020, the Danish Utility Regulator published a report which begins as follows:

> The economic regulation does not give the district heating companies an incentive to become more efficient, as the price of district heating in the 'hvile-i-sig selv' regulation is determined on the basis of the company's costs, whereby higher costs are simply passed on in the form of higher heating prices to the detriment of households and companies that consume heat. Although district heating companies may have the goal and focus of setting low prices, they are not pressured to do so by competitors or

> economic regulation (The Danish Utility Regulator 2020, 3: author's translation).

According to the governmental authorities, new procedures and signals such as benchmarking, heat price ceilings, and increasing competition between individual and DH solutions (e.g., the suppression of the mandatory connection on all new buildings) would incentivize the DH utilities' economic efficiency. This, consequently, would result in heat price reductions for the customers (O. Andersen 2020b; J. S. Nielsen 2020; The Danish Utility Regulator 2020). The national authorities seem responsive to a neoliberal rationality, which presumably stems from an underlying assumption that what worked for the electricity sector in the 2000s might also work for the DH sector.

According to the DH proponents, these market-like policies are problematic because they assume that what leads to an efficient DH transition in one site will do the same in another. However, DH systems are anything but similar: DH infrastructures are highly specific to each site, with particular building blocks, size, age, layout, heat production, customers, etc. Kim Mortensen, director of the DDHA, relates:

> If the utilities have to spend all their time and energy on bureaucracy and filling out papers and forms to satisfy the authorities, it will take resources from what their core task is, namely, to provide high security of supply, cheap heat and the green transition. (...) We think that it is far more important to have a debate about the needed measures to ensure even higher utility efficiency. I think that we need the authorities to listen to our desire to break with the New Public Management and retail regulation, and instead focus on having the right conditions for the companies to both provide green heat and to ensure a framework that will enable them to invest and run their utilities wisely to reduce their costs (Kim Mortensen in Andersen (2020a), author's translation).

In conclusion, it appears that there are two contradictory interpretations of 'what is best for society'. On the one hand, the DH practitioners claim that DH inefficiency is the outcome of obsolete regulations based on a security of supply rationality. Therefore, they promote 'modernized regulation' to solve the issue. On the other hand, the national authorities claim that DH inefficiency is the outcome of a lack of market incentives, and they promote market competition to solve the issue.

Although both the socioeconomic calculations and the market efficiency regulations were/are based on a rationality of limiting societal costs by picking the most cost-effective solutions, the two competing rationalities seem to have led to an ongoing struggle between national authorities and municipal/DH actors to impose their own definition of what ought to be done.

Therefore, this controversy and the two sector representations highlight the importance of the interwoven political and economic interests that are co-constructing interpretations, knowledge, and governance assemblages in the provision of DH. It shows that the processes of imposing one's own voice is an ongoing and messy matter, and it seems that the outcome of this controversy may have great consequences for the future low-carbon transition of Danish heat provision.

8.7. CONCLUDING REMARKS

This chapter has discussed the results of the analyses in light of Transition Studies and relational approaches. The latter approach, upon which this thesis is based, has allowed me to move from 'outside' to 'inside' the socio-technical networks and unfold the actions. It, therefore, offers a new account of sustainable energy system transitions. The chapter has revealed that transitions are not the outcome of coherent strategic orchestration, as often assumed in the transition study literature (Kemp and Loorbach 2003; Sovacool and Martiskainen 2020), but rather they are messy and precarious achievements, which are continuously in the making. This also allows one to break away from imposing pre-defined categories onto the field (regimes, incumbents, new challengers, etc.), and to rather see energy transitions, actions, and actors as network effects. This also contributes to reframing the issues at hand from being imposed on the field by the researchers, to being the issues from the field followed by the researchers.

The relational approach has also revealed that energy system transitions are not just a matter of technology diffusion. Technologies appear to be only the visible effects resulting from a long chain of actions, from issue formation, to problematization, and actions with emergent outcomes.

Furthermore, the three studied instances have also revealed that there are not, on one hand, a work of either solely excluding transitions or solely trying to bring about change. Rather, the practitioners seem to engage simultaneously in both 'repair' and 'inventive' work. The three studied instances have also revealed different articulations of devices that assist the practitioners in repair and in inventive work at the same time.

The identification of these two types of work has also built on Callon's (2008) notions of habilitation and prosthesis, which, as we have seen, are two network effects evolving with time. Finally, the last section has discussed the two different interpretations of the field and their underlying rationalities. Altogether, this chapter has explored the results of the three studied instances in detail and has paved the way for the conclusion of this thesis.

CHAPTER 9. CONCLUSION

The conclusion is structured in three parts: the first section concludes on the main findings of the thesis, as well as its contributions to the social science research on energy transitions. The second section presents the limitations of the study, and the third section proposes some directions for further research.

9.1. ACHIEVING ENERGY TRANSITIONS AND THE ROLE OF MATERIAL DEVICES

This thesis has explored three instances of DH transitions. It has shown the different types of work energy transition entails, the diversity of material devices partaking in these processes, the complexity of the interrelations between the different socio-technical actors, and the different transitioning potential that may, or may not, be realized. In all three instances, practitioners are acting in their worlds, trying to reconfigure and stabilize entities from their situated perspectives, and acting and reacting to the uncertainties. The practitioners are simultaneously shaping, and being shaped by, the networks in which they exist.

In all three instances, the energy system transitions are situated enactments: the past developments, the material devices, the socio-professional relationships, the time and place in which they unfold, all are specific elements partaking in the processes. Energy transitions are, thus, neither accidents, nor the result of pre-determined technology diffusion paths. Instead they are the result of multiple and endless adjustments of heterogeneous elements deriving from the actors' attempts to engage in the present while trying to exist in the future. Concretely, the practitioners repair and ensure the maintenance of the large-scale infrastructural energy system, while at the same time coordinate actions towards precarious future alternatives. Therefore, energy transitions result from the dual work of the practitioners who are simultaneously engaged in maintaining a secure energy provision, while (re)acting in their world to create new associations that will, eventually, lead to the desired changes. This view of energy transitions highlights the importance of the mundane (and distributed) work of the practitioners in coping with the complex enterprises at hand and, thereby, it also shows the limitations of using technology diffusion as a unit of analysis.

The three studied instances have also shown that the (often assumed) dichotomy of either maintaining (and perpetuating) the established energy systems, or radically transforming them, is too simplistic compared to the reality of the task at hand. It is not a matter of being either for, or against, a particular future. Rather, the practitioners are trying to 'come to grips' with their worlds and ensure their own futures while adapting to the changes.

My study of the three instances of energy transition has also revealed the means through which practitioners deal with the messiness and uncertainties in transitioning processes. The three analyses have shown that the practitioners create and/or mobilize a diversity of material devices, which provide them new agencies. The devices are used to (among other things) (re)organize heat provision, establish (and stabilize) new long-term cooperations, create shared sources of 'calculativeness', and/or make heat(s) visible. The three analyses have, thus, exposed how a plurality of devices enables the practitioners to maintain the established stability of the socio-technical systems, while simultaneously leaving enough room to engage in new types of organizations, modes of coordination, and associations for attaining desired futures. To this end, the circulation of material devices distributes agency and, thereby, enables (situated) energy system transitions to be assembled.

Furthermore, although the practitioners are calculating and stabilizing their worlds towards planned futures, the outcomes of these actions remain, at the time of writing, unknown and uncertain. Energy system transitions are continuously *in the making*, and the consequences of the actions taken today by the practitioners can never be fully known. The socio-technical network approach chosen in this thesis, with its sensitivity to the role of material devices, shows that transitioning processes are precarious and emergent achievements which can never be fully predicted.

Therefore, this thesis contributes to the social science and energy transition literature. While Transition Studies provides a lens through which DH transitions are a matter of technology diffusion and technological trajectories, my approach has captured transition processes as a matter of griping situations and making futures knowable and actionable in specific ways. Energy system transitions are fragile and situated achievements resulting from the heterogeneous actors' associations and the collective work of simultaneously maintaining and transitioning energy systems. My thesis directs attention to the ways in whcih (energy) practitioners cope with complex (and continuously evolving) intertwined material, organizational, and economic elements. In directing attention to the work of the practitioners and their material devices, this thesis contributes to the existing literature by emphasizing the precariousness and 'ongoing-ness' of energy transitions.

9.2. LIMITATIONS

All theoretical and methodological lenses have their limits, in the sense that they expose some elements clearly while simultaneously shadowing others. Similarly, this dissertation has some limitations in terms of what it can reveal about energy system transitions.

In attempting to capture the practitioners' concerns, uncertainties, and use of material devices in transitioning socio-technical networks, the routines and taken-for-granted procedures (and their influence on transitioning processes) have been left in the shadows. Concretely, everyday work routines, calculations, organizational and/or political factors presumably influence the ongoing transitions, but my approach has not revealed them. For instance, as discussed in section 8.6, this investigation has not addressed the various discourses that influence the actors. While these undoubtedly do have an influence on energy system transition processes, attending to them in detail is beyond the scope of this thesis.

Furthermore, presumably practitioners employ additional material devices to which my approach did not come close enough in order to detect. As I did not carry out ethnographic studies of the practitioners' daily work, it is conceivable that I did not unearth all the devices that assist the practitioners in their work of assembling transition, despite their potential importance in the unfolding processes.

Lastly, I have not investigated the ways in which the devices used have been 'translated'. I did not "*follow the negotiations between the innovators and potential users [of the devices] and (...) the way in which the results of such negotiations are translated into technological form*" (Akrich 1992, 208). Although this would allow one to identify the different ideas and assumptions that feed into the design of the material devices, and to detect how the various practitioners constitute their ambitions, plans, and/or heat customers in particular ways, investigating how the devices were translated was not the aim of this thesis.

9.3. FURTHER RESEARCH

In light of the findings and limitations of this study, there are a number of avenues for further research on the role of material devices in energy system transitions. Ethnographic studies of energy planning at DH utilities would enable one to investigate the translation of the practitioners' observations and assumptions into the making of material devices with specific "scripts" (Akrich 1992). This may enable inquiries into how practitioners attempt to produce other actors (such as other practitioners or customers) as rational economic and/or sustainable actors (Pallesen and Jenle 2018). Ethnographical approaches could enable one to identify more devices than those identified in this inquiry, thereby providing more nuances regarding their role in stabilizing and making the world known.

Future research on energy system transitions could also consider the role of the different forms of expertise mobilized in the problematization of energy production and consumption, i.e., the ways in which the world is made knowable by different groups of practitioners. This could enable one to detect whether some actors/expert groups have more agency in terms of imposing their own problematization (and solution) of concerns. This could reveal political implications regarding who has capacity for action, and what methods or material devices can be used to unlock transition potential.

Further research could also pay more attention to the ways practitioners enact the rules and regulations of energy infrastructures, taxes and investments. As seen in chapter 8.6, DH practitioners seem to interpret the current rules from their own situated perspectives and to enact them with a certain amount of leeway. Delving deeper into the ways in which practitioners mobilize and make sense of regulations could bring insights into the rationalities and modes of governance underlying different groups of actors' calculations and routines.

In conclusion, it may well be worth further research adopting a more ethnographical approach in order to delve deeper into the complexity of the energy system transition *in the making*. Being closer to the practitioners' daily activities and following the emergence of issues and the ways they are addressed by the actors in the field may reveal new insights, which may have implications for our understanding of energy system transition processes.

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APPENDIXES

Appendix A. List of the conducted interviews

	Names	Company	Role	Date
1	Kristian Honoré	HOFOR	Project Leader	11.09.18
2	Thorkil B. B. Neergaard	Brønderslev Forsyning	Director	24.09.19
3	Frederik E. Lynge	HOFOR	Product Developer	29.10.18
4	Søren Dycke Madsen	CONCITO	Senior Consultant	30.10.18
5	Bjarne Munk Jensen	Århus Affaldsforbrænding	Director	08.03.19
6	Peter Jensen	Skanderborg Forsyning	Director	15.03.19
7	Jan Hindsbo and Michal B. Thomsen	CTR	Vice-Director Operation manager	19.03.19
8	Christine E. Sandersen	HOFOR	Energy Planner	14.05.19
9	Per Heiselberg	Aalborg Universitet	Building Energy Scientist	21.04.19

10	Lasse Sørensen	Århus AffaldsVarme	Business Developer Manager	05.09.19
11	Steen Westring	Albertslund Forsyning	Director	16.09.19
12	Lars Gullev Morten Stobbe	VEKS	Director Vice Director	28.11.19
13	Christian Clausen		Inhabitant of Albertslund	16.01.20
14	Hans Henrik Høg	Albertslund Kommune	Chef of the Technical and Environmental Administration	29.01.20
15	Niels Hansen Peter Dyhrholm Andersen	Albertslund Forsyning	Special consultant in energy and administration Energy consultant and technologist	11.02.20
16	Jonathan S. Thordal	Varmelast via HOFOR	Energy Planner	07.04.20
17	Kamma E. Holm	CTR	Director	22.04.20
18	Christian Parbøl	Energitilsynet	Office manager	24.04.20
19	Jesper Troelsgaard Werling	EA Energi Analyse	Civil Engineer	30.04.20

20	Bjarne Lillethorup	Ørsted	Contract Manager	13.05.20
21	Uffe Schleiss	Høje Taastrup Forsyning	Technical chief – maintenance, project and energy consulting	18.05.20

Appendix B. Example of an interview guideline

Interviewee's name, position and company. Date.

<u>Background information</u>

On myself: French, socio-technical approach, bachelor in Geography (social sciences). Summary of the PhD project.

On the interviewee: Background, CV, former position/company, today's main responsibilities and tasks

<u>Historical developments:</u>

- Of Greater Copenhagen heating infrastructure
    - Since what? Issues at stake? Whom and how?
    - Role of the regulations?
    - What have been the relations between X and Z actors? Legitimacy? Negotiations processes?
- On which premises has this institution been created?
    - How does it work?
    - How does it calculate the future?
    - Which tools and technology catalog outlooks are used?
    - What major differences has it provoked?
    - What it to simulate market conditions?
    - Does it take into consideration "system optimization" and if yes, how is it calculated?
- Does the institution take climate change into account?
    - Since when?
    - How is climate change calculated?
    - Are there proponents of technological change?
    - Is there particular forum where you meet and discuss about future projection?

<u>Contracts between heat producers and heat suppliers:</u>

- What is taken into account in these contracts?
- What time perspective do you use? What prices? Costs? Taxes?
- How do you calculate the future and the development of uncertainties in these contracts?
- How often are they re-invested?
- What levels of confidentiality?
- How do you make sure that the other actors do not leak information?
- Does the regulation facilitate possible litigation?

Administrative mechanisms:

- How has which rights of using X technology?
- Where are the rights negotiated and written?
- How can you ensure that the benefits are well-distributed?
- What enables you to see how much benefits you get from each new investment?

External collaboration:

- At what time did this collaboration started? On which premises?
- Has the purpose of the collaboration evolved over time?
    - Is there main difference between the first and the second iteration of the project?
    - To whom are the results addressed?
- How are the plans and report written?
    - Intern collaborations, tools, software?
    - External collaboration, confidentiality, meetings?
    - What is the role of X actor?
- How do you agree on what technologies are to be prioritized?
- How do you assess the sustainability of each resource and decision?

Whom else may I contact:

- If I want to know more about X technology?
- If I want to know more about X organization?

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-933-6

AALBORG UNIVERSITY PRESS