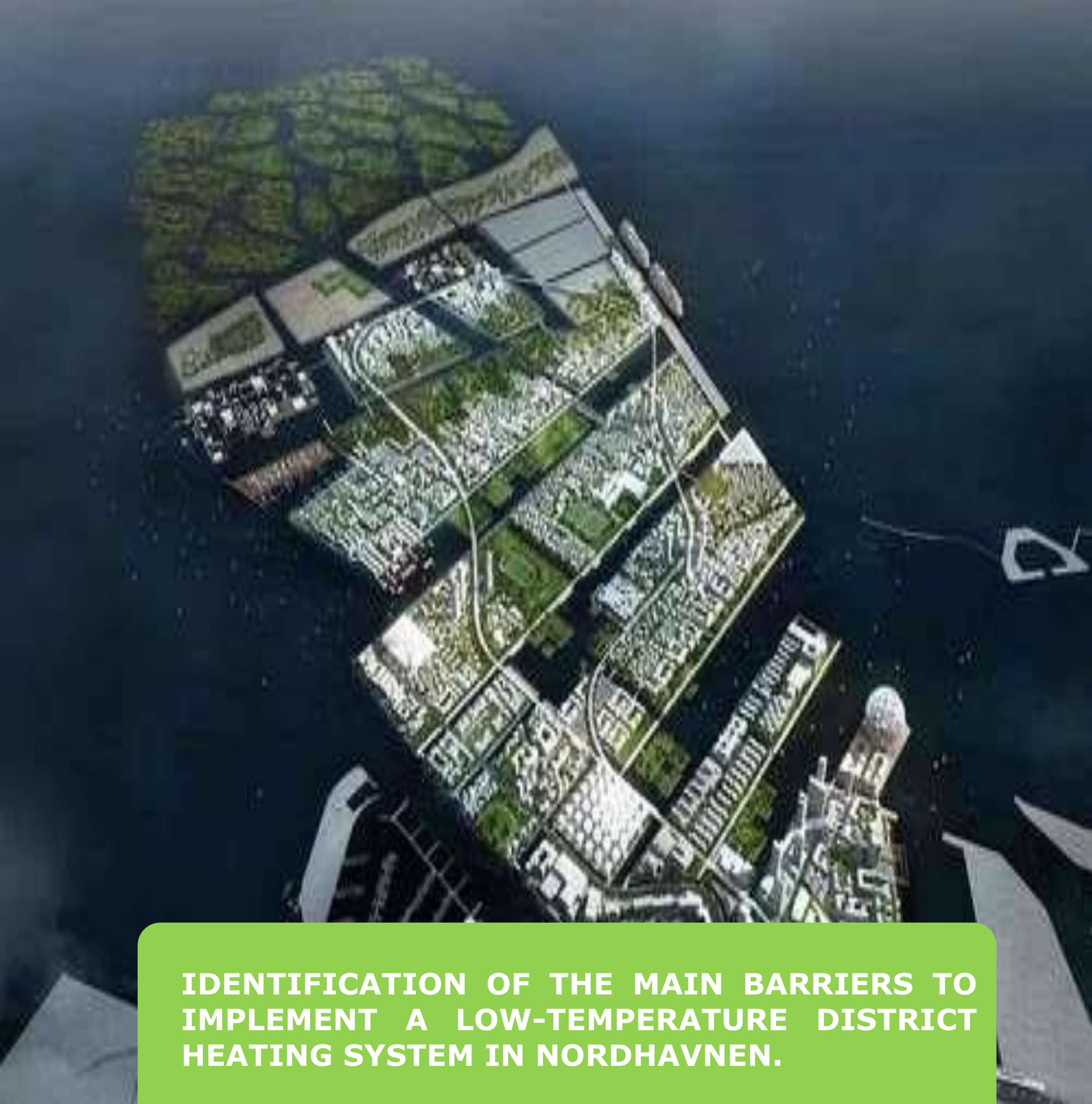

IDENTIFICATION OF THE MAIN BARRIERS TO IMPLEMENT A LOW-TEMPERATURE DISTRICT HEATING SYSTEM IN NORDHAVNEN.

PABLO NAVACERRADA BUSQUETS

FOURTH SEMESTER PROJECT – MSC THESIS, SUSTAINABLE CITIES

SUPERVISOR: MAT-BRITT QUITZAU

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Aalborg University Copenhagen

AALBORG UNIVERSITY
COPENHAGEN

Aalborg University Copenhagen

A.C. Meyers Vænge 15

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Supervisor(s):

Maj-Britt Quitzau

Group number:

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Group members:

Pablo Navacerrada Busquets

Summary:

Currently Denmark aims at phasing fossil fuels from the energy sector by 2050. In that regard, new district heating technologies must be incorporated to energy systems in order to contribute to this goal.

Nordhavnen can offer the opportunity to experiment with the technology operation before the implementation phase in a larger scale. Along this study, the multi-level perspective will frame the focus into analysing the regime of district heating to understand transitions.

Therefore, this study identifies the main barriers that can result from implementing such a technology that can hinder transitions.

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ABSTRACT

The rise of CO_2 levels worldwide associated to negative effects from climate change as a result from human activity, mainly from combustion of fossil fuels, is urging cities to plan energy systems in a sustainable manner. At the light of this challenge, Denmark is aiming at becoming fossil fuel free by 2050 and that entails current technologies at the energy sector will need a shift to green and more efficient ones. This transition will be marked by new district heating technologies that will replace the obsolete systems. In fact, a low-temperature district heating can reduce heat losses thus saving energy fuels, while at the same time providing both comfort temperature and a good distribution of hot water service. Furthermore, implementing this technology means great opportunities for other technologies that can take advantage of this low temperature characteristic. Therefore, heat pumps and geothermal energy can potentially play a key role in the future energy systems as a result of lowering down the supply/return temperatures in the distribution of district heating. This will contribute to more efficient, less polluting and more renewable systems. Nevertheless, there are some technical considerations that might challenge this implementation.

In the present study, it is been discussed what are the main barriers to implement a lower temperature district heating system in the area of Nordhavn with a further potential implementation in Copenhagen, Denmark. Currently, Nordhavnen is hosting an energy laboratory which is trying to find out these specific barriers. In line with this, the Danish Government is supporting this initiative in order to achieve an energy sector fossil-free on time where technologies such as a low-temperature district heating can be born, mature and flourish. For that reason, this study provides an answer to that by following the multi-level perspective in which four dimensions from the regime of district heating are identified and analysed: technology, policies and markets related and cultural mind-set. These dimensions interplay crossing each other, complementing and supporting the overall understanding of the district heating regime and giving shape to its trajectory over time. Danish history and cultural background can indeed help to shape the right policies trough institutions, leading to the development of the technology in which the market operates.

The findings show that both systems will co-exist and a slow process of adaptation would take place. Integration will be challenging due to the fact that current heat distribution network would have to support both systems with different supply/return temperatures. In addition, to maintain the same heat difference between supply/return pipes as in the current system will demand new tariff regulation, also adapted to new residents. Nevertheless, Nordhavnen can provide important lessons to understand better new implementations and how these processes work with the objective of contributing to phase out fossil fuels from energy systems in the future landscape.

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DEDICATION

To my parents who have always offered me great support and trust.

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PREFACE

Personal reflection about "waste" in cities (in particular in energy)

Nature is wise. It operates as a perfect cycle where no waste is produced at all. Everything is well connected and part of something else, entangled and rooted in systems and subsystems called ecosystems that make the most of each of its components. Cities or urban settlements are also included in the definition of ecosystems, as the result of the interaction between energy and matter which flows and is exchanged in 360 directions. The difference between the former and the latter systems is that whereas in cities there is talk of *recycling of waste*, in natural environments that concept does not exist. CO_2 cannot be understood as an animal´s by-product since it represents an important source of energy for plants together with sun light. On the other hand, for the rest of eukaryotes from the animal kingdom, oxygen which is released by plants (their by-product) makes possible for us to function by activating our metabolisms. Here it can be seen how the loop is effectively closed and therefore the notion of recycling is a human invention and a substitute for efficiency in systems without waste such as natural ecosystems. No by-products then. Thereby, talking of waste it is just a point of view. Nature regulates itself and is self-managed as a result of a co-evolution along time with its different subsystems and subcomponents.

However, humanity is not capable of closing all the loops and neither to connect all the gaps in cities by linking energy and matter in a perfect cycle as nature does. Nevertheless, there are some attempts: Faeces from pig herds can produce large amounts of gases which have the potential, if treated adequately, of electrifying a whole bus network of a small city. Another example can be the organic waste generated at our homes which is capable of producing heat through incineration at power plants and be distributed by a district heating network. In this case, CO_2 resulted from the burning process was already out there, so the net balance is not altered since it does not come from fossil fuels. These cases illustrate an attempt from human beings to approach to the good and efficient practices of nature. Or, in other words, these examples are sustainable practices which aim at achieving synergies across different sectors in cities, contributing therefore to the energy system. Urban development then becomes crucial to achieve a proper integration of all the subsystems of a city such as transport, energy, water, buildings, etc. in order to provide quality and resilience of efficient services in cities (World Bank, website); just as in nature.

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This thesis represents the hard work of two years in which I left my country in order to continue with my education. During this period of time, I had great support from many people:

I would like to thank all the support that I received from my partner Paloma who have really found a good way to team up with me. In addition, I would like to extent my gratitude to my friends back in Spain and the new ones from Denmark, especially to Martin for our great adventures.

Many thanks for all the International Project Management team, especially to Isidore and Patrick who contributed with their dissertations to inspire me. In addition, I would like to thank my supervisor Maj-Britt who remained not only supportive but consistent in feedback and guidance during this demanding period in which managing time resources was so important.

And with utmost sincerest gratitude to Club Alpino de Ciencias for giving me the opportunity to meet great people, experience amazing trips, and good climbing.

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ABBREVIATIONS

4GDH	4th Generation of District Heating
ΔT	Delta temperature
AAU	Aalborg Universitet
ATES	Aquifer Thermal Energy Storage
CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CPH	Copenhagen
DERA	Danish Energy Regulatory Authority
DH	District Heating
DHW	Domestic Hot Water
DTU	Danmarks Tekniske Universitet
EH	Electric Heating
EUDP	Energy Technology Development and Demonstration Programme
HP	Heat Pump
ICI	Informal Conversational Interview
LTDH	Low – Temperature District Heating
MLP	Multi – Level perspective
NGO	Non-Governmental Organization
PV	Photovoltaics
TSO	Transmission System Operator
SH	Space Heating

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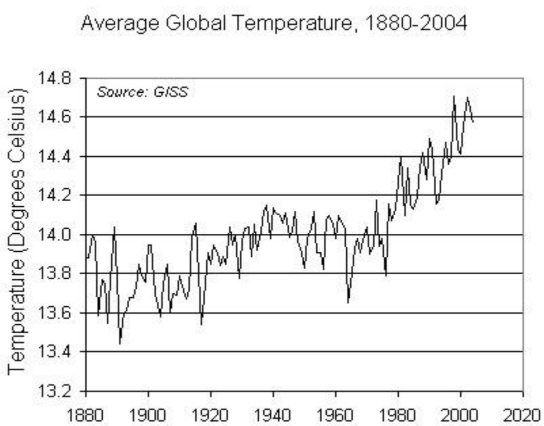
1. Introduction

From urban development towards sustainable development

In the face of sustainability challenges, climate change appears to be the one of the most complex ones. This global climate alteration, resulting from the increased atmospheric concentrations of carbon dioxide (CO_2) by more than a third relative to pre-industrial levels (Kotchen, 2007), gives evidence of the influence of human actions on biophysical ecosystems. This leads to conclude that humanity have entered a new planetary era best described as the Anthropocene due to the vast negative impact human beings are having on planet Earth (ibid). CO_2 emissions, produced by humans in larger scale, are responsible of the increase of temperature worldwide by about 0.8° Celsius (1.4° Fahrenheit) since 1880 which has changed the Earth temperature balance, thus affecting oceans, atmosphere and lands (earth observatory-NASA).



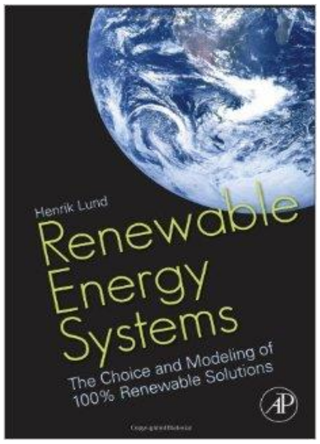
Picture 1: Average global temperature - Source: Earth policy institute

In this context, the role of cities as major consumers of energy and as main polluters is more important than ever. It forces us to be concerned about how cities can be planned in such a way as to be more energy-efficient (Breheny, 1992). In this way, cities and megacities have the potential to achieve larger savings of energy and consequently achieve at the same time a reduction on the emissions of CO_2 by setting the right systems that will allow societies to thrive and to fight climate change. In addition to CO_2; NO_2 and CH_4 are also greenhouse gases resulting from the burning of fossil fuels such as oil, natural gas and coal which are the leading cause to the increase of temperature worldwide (www.acs.org). Thereby, this reliance on fossil fuels hinders a transition towards renewable energy systems. Nevertheless, technologies such as district heating for instance are a good point of departure in many countries at high latitudes, to start transitions into better and more efficient energy systems that can lead to energy savings and therefore to CO_2 reductions. But, transitions are not always facilitated and several changes must occur in order to reach a society with potential to escape from fossil fuels.

All the above lead to the urgency of changing our current energy systems, and urban planning can make a difference in this regard considering investments for the long run. Several pressures, such as increasing CO_2 levels leading to health problems, climate adaptation programmes, changes in agricultural yields and many other effects, on the current landscape can trigger urban responses (Hodson, 2010) to configure the social and technical organization of infrastructure systems in cities.

Picture 2- urban planning Source: www.fajarservices.com

In this line, it becomes relevant to define urban development as the way of organizing urban infrastructures such as sewerage system, water supply system, electricity and heating systems, transport system, buildings, etc. A perfect interrelation and integration across these systems is then imperative to achieve efficient and sustainable individual systems such as the energy one. For that reason, it is of paramount importance to establish synergies across the systems because it can lead to reducing "waste or by-products" in the overall system and to design an efficient urban ecosystem among humans and natural resources.



Some examples of synergies can be found in the literature: (1) the district heating network which supplies heat to dwellings is based on the distribution of hot water through insulated pipes, both to heat the dwellings and to provide hot water (Lund, 2010); (2) electrification of the transport fleet through electric vehicles (Lund, 2008); (3) low-energy buildings as key pieces of the smart energy systems (Lund, 2014); (4) or as it was mentioned before, using the organic waste to generate heat through incineration (Sahlin, 2004). All these synergies have a common denominator: energy is present in all of them and therefore great improvements are possible within the energy sector by identifying the right links in order to close the loops. In fact, a shift from urban planning to sustainable urban planning is needed to face one of the major environmental challenges of the XXI century, namely, climate change.

Picture 3 - Renewable energy systems. Cover from the book of Henrik Lund

Sustainable planning

In this transition towards fossil-fuel free energy systems, sustainable planning can play a decisive role. The broad concept of sustainability entails a holistic integration of the components of a system that is endurable along time. In the line of this definition, a sustainable system is that one that does not require any inputs from the outside to make it works. Self-sufficient concept, also called "*autonomous or stands alone*" (Marszsal, 2011) then becomes the essential point to provide the system everything it needs.

With this said, cities have to be both producers and consumers equally balanced and an effort from the policy level must be made to reach sustainable urban ecosystems. Nowadays urban governments are increasingly adopting transition policy discourses and actions, as the security of ecological resources and climate change have become issues at the urban scale (Quitzau, 2012). With a similar perspective McCormick et alters (2012) state: "there are few powerful initiatives that are decisively shifting urban development in a sustainable, resilient and low-carbon direction". They also state that governance and planning are the best tools to be used in order to catalyse, intensify and accelerate urban transformation, including the energy sector. Furthermore, from 1987 and with the first definition of sustainable development from the Brundtland report, more special focus was placed on renewable energies to have a more important role in energy systems in order to transform them.

In summary, there are several reasons that lead to conclude that planning as it is conceived today lacks the necessary tools to reach a city development that can be called sustainable per se. However, this is not the aim of this report. On the contrary, this project is focused on new ways to unlock current energy systems from fossil fuels.

Low carbon society

Fossil fuels are a finite resource on the planet, which generate significant quantities of carbon emissions (CO_2) when combusted for power generation, contributing to global warming and climate change. Fossil fuels as a non-renewable finite resource are diminishing with use resulting in steadily increasing energy costs and potential security of supply issues for countries in the future (McCormack, 2013). In consequence, unsustainable systems or regimes have been established with a large dependency on other regimes in terms of energy imports leading to one main conclusion: The fossil fuel infrastructure legacy constitutes a heavy burden for countries and investments on alternative energy sources are often dismissed.

Picture 4-fossil fuels Source: thinkprogress.org

Due to the negative impacts derived from human civilization, the dramatic rise of CO_2 emissions and other greenhouse gases with the subsequent unprecedented change in the "global chemistry of the planet" (Caravalho, 2011), today we are living in a moribund fossil fuels era. There is wide consensus that mankind has already reached the oil peak which means the maximum rate of extraction of petroleum is been reached and from now on a decline on extraction will be observed. Thereby, in order to avoid a collapse of the industrial civilization, the remaining stock of fossil fuels must be used in smart and effective ways that allow societies to start a transition to cleaner energy technologies (ibid). This process is called low carbon society, and counts with three key points that must be addressed: renewable energy, energy storage and smart grids. On those pillars we must build a future energy system and all efforts must be made to promote them.

In the light of these challenges, the Kyoto protocol (1992) established a set of rules countries and governments might accomplish an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCC), which commits its Parties by setting internationally binding emission reduction targets as the basis for a global response to the problem of climate change. *"It is a widely accepted fact that the future energy system will be considerably influenced by the climate change problem"* (Russ et al, 2007).

In summary fossil fuels (gas, coal and oil) were set as the base for the energy systems in most of the societies with little concern about alternatives. This habit of relying on fossil fuels to power countries' economies will be continued until well into the 20th century. There are, however, some countries that are developing energy road maps and several strategies, energy milestones, goals, etc. with the purpose of getting rid of fossil fuels for their future energy systems as is the case of Denmark.

Denmark towards independence of fossil fuels

Energy systems

With the Brundtland report in 1987, energy systems started to consolidate themselves globally as long as new technologies appeared or were developed. By combining fossil fuels and other sources (nuclear, biofuels…) with renewables, energy systems began taking shape and have allowed a secure grid for a large segment of the global population in the last 50 years thus contributing to sustainable development. However, the global energy mix has depended so much on fossil fuels which as it is known are not sustainable in time.

In this context, Denmark provides a unique energy landscape due to the fact that the whole nation is aiming at becoming fossil fuel free by 2050 as consensus was reached in the energy policy agreement of 22 March 2012 (energy policy report, 2013). Therefore, the choice of Denmark as an energy model entails good understanding of an excellent urban planning together with energy planning. Before getting deeper into the Danish energy system, it is relevant to define what an energy system is. In order to do it, examples of the energy interactions in the Danish case will illustrate the concept.

An energy system comprises mainly three main subsystems or sectors, namely: *electricity* sector, *heating* sector (can include *cooling*) and *transport* sector. A successful interaction and integration among them leads to great efficiency which in the long run is very positive because it will lead inevitably to energy savings and thus to a CO_2 reduction as stated before. It is then imperative to develop efficient energy systems in order to face climate change challenges. That calls for smart energy systems, so "smart electricity, thermal and gas grids can be combined and coordinated to identify synergies between them in order to achieve an optimal solution both for each sector as well as for the overall system" (Lund et al, 2014).

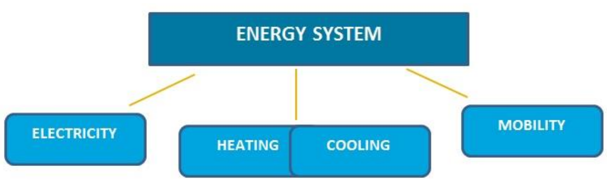
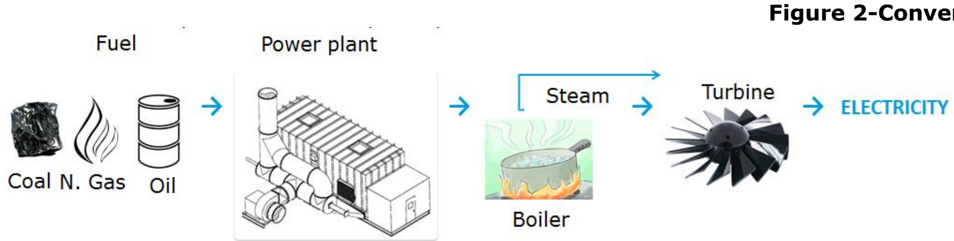


Figure 1-Breakdown of an energy system into the energy sectors

Electricity mainly comes from power plants, excluding renewable energies. In a conventional power plant (as it can be noticed below), the plant needs fuel to operate. The fuel, as it can be "fossil" as coal or renewable as it can be biomass, is burnt in order to generate a high temperature which makes the water to boil. Once this happens, the water turns into steam that will move a turbine and thus generate movement which converts this mechanical power into electric power (relative motion between a magnetic field and a conductor). One peculiarity of the process is that during the thermal conversion, not all the energy can be converted into mechanical power due to the second law of thermodynamics. That means that there will always be some heat losses (by-products) to the environment. District heating systems as the ones in Denmark can take these heat losses from industrial activities and from power plants (cogeneration power plants) and now they can produce both electricity and heat. These cogeneration power plants or combined heat and power (CHP) are the main actors in charge of distributing heat on a District Heating network. In conclusion, the benefits of a CHP plant can be seen in the energy savings: the lower the heat it is supplied, the less fuel will be needed in the system to be burned.

Figure 2-Conventional power plant



If we take the Danish case for instance, it is possible to observe fossil fuel dependency nowadays. In that line, as per the figure 3 below, the CHP (Combined Heat & Power) model allows to take advantage of conventional power plants to produce both heat and electricity thus contributing to a very efficient synergy across both sectors.

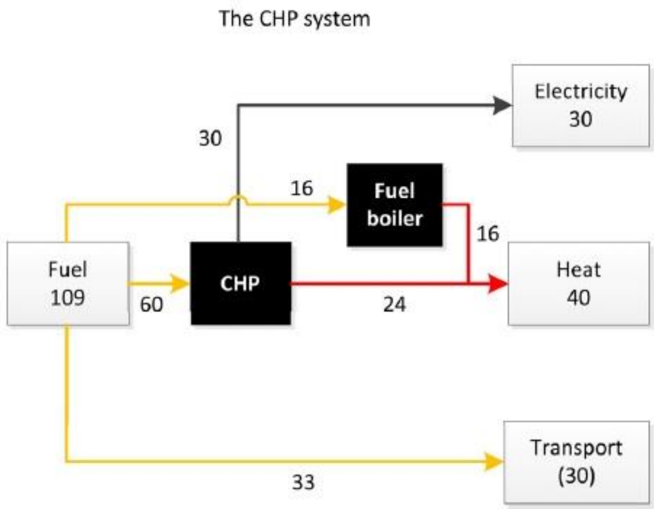


Figure 3-Breakdown of the Danish energy system (Mathiesen, 2013)

If fossil fuel independence is wanted to be achieved in Denmark, then fuel inputs in the system have to come from renewable sources such as biofuels. As it can be observed in the picture below, both electricity and heating sector are very interlinked in smart energy systems. In that way, **demands** represents the sectors which are supplied, **conversion** depicts the transformation from one sector to another through different technologies, and **resources** show the generation source. The perfect integration of technologies thereby makes possible a low utilization of fuels, mainly biofuels, and an efficient reuse of all the energy by-products from all the spots in the energy system thus becoming fossil fuel free.

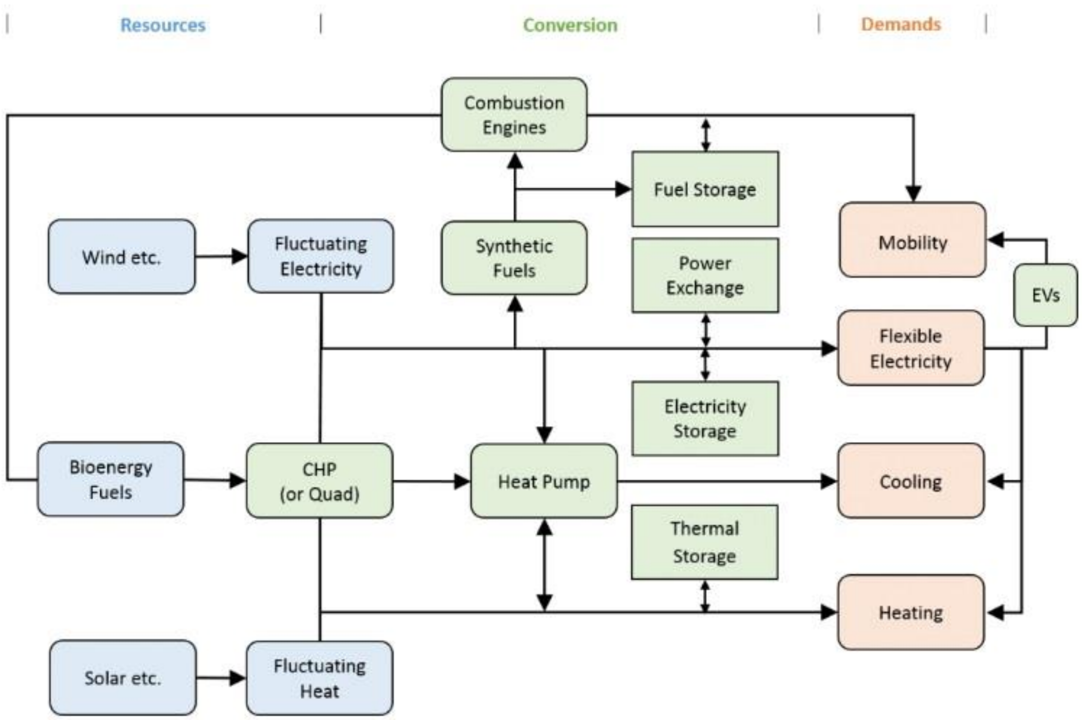


Figure 4-Smart Energy system Source: EnergyPlan.eu

Returning to the concept of smart energy systems, the Danish system is investing in many efficient technologies, including renewables energies and conversion technologies thus contributing to achieve more flexibility in the overall system. Nevertheless, it is the heating sector the one that has more potential to be transformed in Denmark as well as in other nations.

Heating sector

Narrowing down to a particular sector of the energy system, namely the heating sector, it is possible to explain in more detail how one subsystem works. In this line, a new goal in Denmark was defined: both electricity and heating sectors are expected to become fossil-fuel free by 2035 (DEA).

The supply of heat in Denmark is characterized by the application of district heating systems. This singular technology is based on the principle of economies of scale in which it is more economic, easier to maintain the equipment and technically simpler to install several connected heat supply units, rather than individual units. By using a shared technology rather than individual ones, total installed capacity can be reduced and thermal energy can be produced and distributed to supply customers both heating and production of domestic hot water.

There are more than two and a half million domestic heating installations in Denmark and around one and a half million (60%), are district heating installations. Thus, district heating dominates the heating scene of Denmark (DEA). Today, about 80% of DH is co-produced with electricity, also called co-generated heat and electricity and is one of the most energy efficient and environmentally friendly ways of producing electricity and heat (ibid).

The most peculiar characteristic about district heating systems is the possibility of using surplus energy (heat) that would otherwise be wasted. Any potential heat by-product in the entire city can be used for a common network as district heating is. According to DBDH, district heating system utilizes the heat from a wide variety of energy sources such as combined heat and power plants / cogeneration (CHP), surplus heat from the industry, large solar thermal systems, geothermal heat and large-scale heat pumps. This flexible system configuration ensures an optimal and reliable energy supply, increases efficiency and reduces fuel costs (DBDH).

<u>District heating operation</u>

When heat is generated at the CHP plant for instance, it distributes it for heating and/or cooling residential, commercial and institutional buildings, and for industrial processes. Ramboll A/C, one of the leading engineering consultancies in Denmark and Scandinavia which provide district energy services, identifies three main elements in district heating systems, as it can be observed in the picture below:

- Production: A thermal energy plant which can incorporate Combined Heat and Power (CHP) plants and which uses either fossil fuels, recuperation fuels of renewable sources as energy sources.

- Distribution: A network of pre-insulated pipes that carry (water as heat carrier) the thermal energy from the plant to buildings.

- End of the chain: The interface with services at the building including space heating, domestic hot water services, cooling and process heat.

District heating in essence offers
A unique way of utilising surplus heat from the existing energy system
An early and easy option of introducing more renewable energy into the energy system

Table 1-District heating benefits Source (Moloney, 2011)

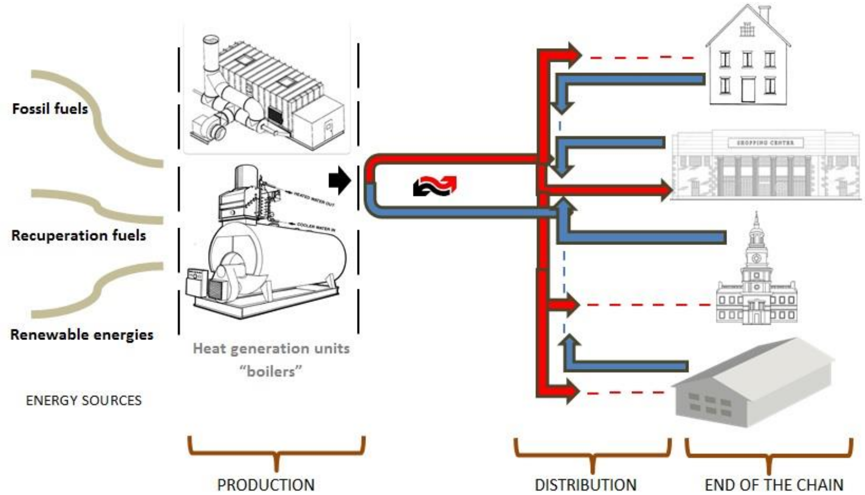


Figure 5-district heating network and elements

In summary, district heating requires low-temperature hot water which is the energy carrier through the pre-insulated pipes. The lower temperature for the system the better, as long as the temperature gradient is enough to exchange heat (from higher to lower temperature) with the user end.

In order to continue with the goal of the Danish Government of phasing out fossil fuels by 2050, energy technologies not only need to be efficiently integrated, but also they need to evolve to reduce fuel consumption and to allow more intermittent renewable energies in the energy system. In fact, the 2025 Climate Plan, created in 2012, proposes to make Copenhagen (Denmark´s capital) the world's first carbon neutral capital city. Therefore, the city must use less energy than it does today and at the same time divert energy production to green energy (2025 Climate Plan, 2012). The same plan also recognizes the importance of wind power to electrify the system step by step by integrating more wind into the system. In this line, technologies such as district heating and wind power become essential nowadays for these green transitions.

There are examples of these transitions in the past, specifically energy transitions studies that have conducted several analyses in order to comprehend the role of transition processes and its components: The Dutch electricity system for instance was studied through the trajectory of technical developments, changes in rules and visions, and social networks that support and oppose renewable options. These options, among others, are renewable niche-innovation trajectories (wind, biomass, PVs) and provided lessons about socio-technical dynamics, problems and windows of opportunity (Vergong and Geels, 2007). Also in the Netherlands, there was a study of the historical perspective of Aquifer Thermal Energy Storage (ATES) with the purpose of analyzing the main barriers of applying ATES to store seasonal energy in buildings through several projects at the building scale (Coenen, 2010).
This description about the energy sector and more specifically in the heating sector in Denmark leads to understand the current situation and therefore to introduce the problem area of this report.

Problem area

In the light of new and green efficient technologies that can contribute with these ambitious energy goals such as becoming fossil fuel independent, there are some initiatives that can help in such a transition.

In order to reach green energy transitions, energy researchers from Danish Universities such as DTU (Danmarks Tekniske Universitet) and AAU (Aalborg University) state that the existing district heating system must be changed radically towards lower temperature district heating networks, identifying buildings as key pieces of the future smart energy systems (Lund, 2014). In order to achieve so, societies must jump into the latest district heating technology, the so called the 4^{th} Generation of District Heating (4GDH) according to many experts in the matter (Werner, Söderholm…). It can offer the many opportunities Denmark and many other countries are waiting for in order to achieve a fossil fuels–free energy system.

Picture 5- EUDP logo

The necessity of escaping from fossil fuels leads to look closer to initiatives in Copenhagen such as the energy laboratories which provide urban spaces to experiment from an energy perspective in general and a low-temperature district heating network in particular. EUDP (Energy Technology Development and Demonstration Programme) which is supported by the Danish Government in order to achieve an energy sector fossil-free on time is in charge of the research and demonstration project EnergyLab Nordhavn. The project can show how electricity and heat, energy efficient buildings and electric transport can be integrated in an intelligent and optimized energy system. Around 49 projects must now develop and commercialize energy technology products and solutions which include integrated and flexible energy markets, coordinated operation of the electricity and heating system, energy storage, low energy buildings here and now optimized in relation to energy markets and technologies with flexible switching between sources (DEA). Nevertheless, it is important to distinguish the energy laboratory as a whole and one particular experiment within the laboratory which is the energy tests for potential implementation of a low-temperature district heating system.

Following this, the problem area of this body of work can be presented:

Nordhavnen

Nordhavnen (North Harbour), as stated before, is holding an energy laboratory where new heating technologies such as a low-temperature district heating can be tested. Located at the Øresund coast, in the North-East part of Copenhagen, Nordhavnen´s Energylab has the purpose of analysing the barriers and challenges this new technology might present, so they can be taken into account for further implementation in the near future.

Nordhavnen also represents the future sustainable district of Copenhagen in the next 20-40 years. Therefore, not only cutting edge energy projects are expected, but also several sustainable practices regarding mobility, urban spaces, etc. will take place in order to accommodate to 40-50.000 future inhabitants.

Nevertheless, a future implementation of a low-district heating temperature implies several challenges. For example, there would be a system incompatibility regarding the existing district heating system. Both of them will co-exist until the new system, namely a low-temperature district heating system, will replace the existing one. Elaborating on that, this represents an important challenge, especially when nowadays an existing district heating system is fully operational and efficiently working with the many synergies across the energy sector as it has already been seen. In addition to that, tariffs will have to be adapted to the new residents due to the new technical conditions from the new system, resulting from several difficulties such as respecting the same temperature difference between supply and return pipes, as it is today. **Picture 6-Nordhavnen Source: Ramboll.**

The new technology objective in Nordhavnen is to reduce the supply temperature from 70°C to 50°C regarding supply pipes and from 40°C to 25°C concerning the return ones, to the level that still guarantees:

- The delivery of DHW with the required temperature of 45-50°C district heating water at the tap.

- The design indoor temperature in the buildings, usually 20°C of operative temperature (thermal comfort) (Brand, 2013).

Picture 7-Guarantee of service

The Danish´s goal of phasing out fossil fuels from the heating sector by 2035 is the very first argument for investing in such a technology. Secondly, the application of a low-temperature district heating system will lead to an increasing number of low-energy and refurbished buildings with reduced heat demand. And last, but not least, the heat supply of buildings were originally designed for medium supply temperatures, so it is very possible to adapt them to the new system (Ibid). Implementing a low-temperature district heating system also entails great opportunities for other technologies that can take advantage of this low temperature characteristic. Therefore, heat pumps and geothermal energy can potentially play a key role in the future energy systems if technologies such as the so called one are implemented. All contributing to more efficient, less polluting and more renewable systems.

Thus, considering all the above, in the present study, it is discussed what are the challenges and main barriers to implement a lower temperature district heating system in the area of Nordhavn with a further potential implementation in the Danish capital. It will be supported by a description of the current district heating regime which will contribute to understand the major implications that this new system might have on the current one. In addition, an evolutionary explanation of the district heating regime will be presented in the context of an energy transition towards phasing out fossil fuels from the Danish energy system. Therefore, the Danish district heating trajectory is analysed in this body of work in order to identify such challenges.

To guide the report, the district heating system will be contextualized in the multi-level perspective theory in order to shape and frame it. After this and through the use of research methods such as energy reports, energy articles, etc. and interviews to several relevant energy actors, 4 dimensions of the district heating regime will be presented and analysed. At the end, a final framework is achieved to identify the main barriers and challenges of implementing a low-temperature district heating in Nordhavnen and later in Copenhagen.

2. Theories

Energy regimes are complex systems that are characterised by large firms, public bodies and economic interests. It can be said that all these actors define the set up and shape of the current energy systems everywhere. Zooming in to a district heating scale, it is possible to find those characteristics as well. However, transforming systems can be a slow process that can require several changes before shifting from one system to another. In fact, by making changes on both the energy system and the district heating system not only requires technological innovations, but also a combination of elements such as social acceptation, support from small networks of actors and a constant pressure on the current regime in order to alter it. Urban pressures must have urban responses in that regard (Hodson, 2010) and the CO_2 pressure is forcing current technologies to develop, resulting in efficient and green energy systems.

Energy systems can evolve slowly following an "unfolding process" with continuous improvements making the overall system better and more efficient as occurs in nature cycles. That is the case of the evolutionary view of technological transitions (Geels, 2002) in which creating new configurations can result in new paths and trajectories. For instance, the case of district heating technologies which have been evolving from the last 100 years from outdated systems to better and more efficient ones by lowering temperatures and improving the technologies involved. However, when is it good timing to jump from one obsolete generation of district heating to the next one? Or in other words, when is the best time to un-lock the existing system?

On the other hand, it is important to take into account that technology investments can cause an "ironclad" contract with society that in most of the cases forces to maintain a system during its technological lifetime, so investments can be recovered. Unruh defines this concept as the combination between technology and institutions, both creating a complex system that locks-in society with a single technology with very few opportunities of escaping from it. Lock-in therefore results then from the regime´s path dependence (succession of events) and thus makes difficult to dislodge existing systems. An example can be nuclear power. Such a great financial and structural investment requires that a technological shift might be very difficult to consider. Long time will pass until the system will be ready to move on and evolve to a different one in which generation of energy is coming from other sources.

In the present study, it is discussed what challenges can be found in order to implement a lower temperature district heating system in the area of Nordhavnen and how would it coexist with the current district heating regime. Along this chapter, some theories will contribute to give shape and to bring light to the problem area. In this line, to justify which theories are important to the problem area is imperative in order to frame the project context as it can be seen in the picture below. It was found relevant and interesting to dig into:

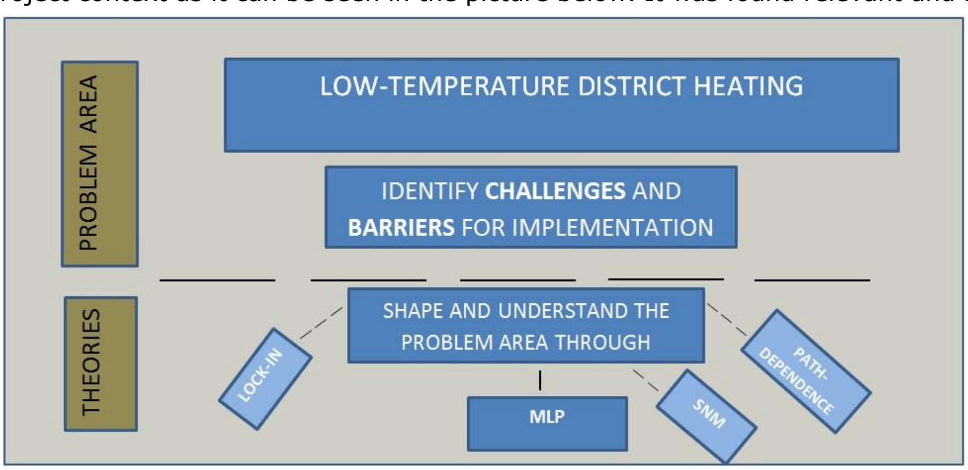


Figure 6-Theories in the report

- *Multi-level perspective (*MLP*)* to understand the three levels in which new innovations and technological improvements have to go through, namely niches, regimes and landscapes. In this way, a better understanding of the district heating context both in Nordhavnen and Copenhagen in Demark can be achieved. More in particular, about how the actual regime works and how the past of the DH technology through its history and trajectory has influenced it. This will help to set the base to better perceive today´s transition of district heating towards fossil-free heating systems.

  Within MLP we can find some interrelations with other theories that supplement it as it can be observed in the figure 6 above in dotted lines:

  - *Local niche experimentation* within Strategic niche management. As Nordhavn is preparing an energy laboratory, so energy experiments can take place there with the purpose of testing energy innovations to further upscaling in case of success. It is also related to MLP where development of niches is imperative to create transitions.
  - Lock-in and Path dependence to guide the study and because its interrelation with MLP.

Energy transitions from a multi-level perspective

When talking about transitions, it is mandatory to mention the multi-level perspective theory to understand interactions between technology, policy/power/politics, economics/business/markets, and culture/discourse/public opinion (Geels, 2011). *In this project, MLP is used in two ways: on one hand, to understand how niches develop from a real pool of niches germination as it is Energylab in Nordhavnen; and on the other hand to take the regime of DH in Copenhagen to explain future changes that goes hand in hand with one niche experiment, namely a low temperature DH network.*

MLP is a middle range theory that entails navigation between three analytical levels by climbing up from the lowest and less stable to the highest and more stable level in socio-technical systems as it can be seen in the picture below.
When all the elements come aligned and stable, then it can take advantage of the windows of opportunity created by changes and modifications on the general landscape. Furthermore, establishing a new niche with a new technology can create inertia to change (Unruh 2002 citing Farrel and Saloner, 1986) and penetrate into the next level.

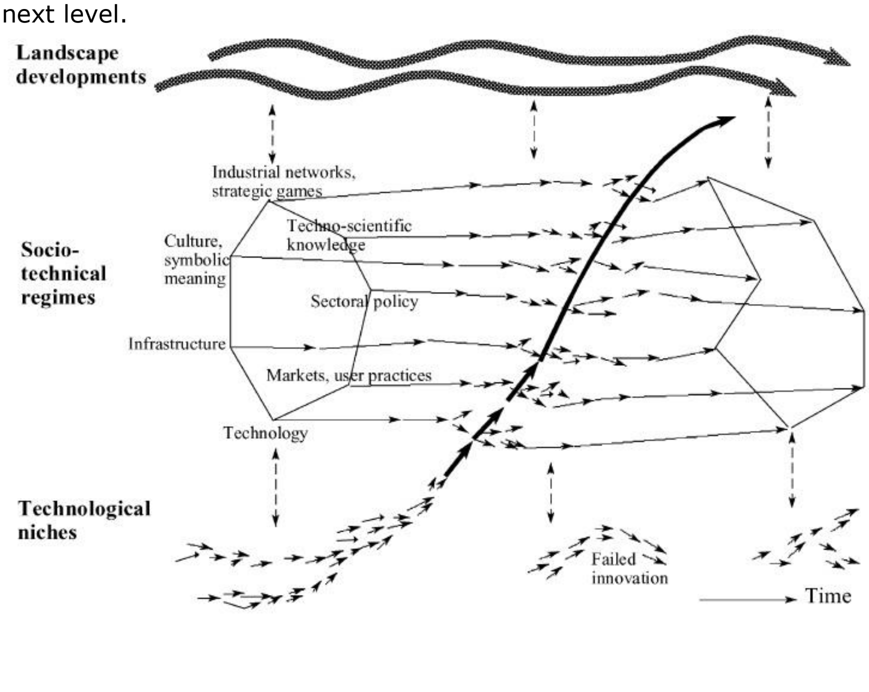


Figure 7- MLP a

Source: Geels, 2002.

In the figure 7 above it can be seen the relation between niches trying to breakthrough into the regime and change the overall landscape. However, to comprehend properly this theory it is more appropriate to deconstruct its components:

- Niches

A niche is the space an element occupies on a system with a defined function and role and it is of paramount importance to understand "adaptations" in the regime. Therefore, new niches can be generated by the replacement from old ones which in practice means replacing roles and functions. In natural environments, ecological producers such as plants are less easily removed and replaced by other beings that can provide the same ecological services. The niche they occupy is the result of a co-evolutionary process as occurs in lock-in processes as well. Instead, rabbits as the bottom of food chain as primary consumers can be replaced from other mammal species in the long run if natural selection operates in such a way. It means the best adaptation to a specific environment survives. Thereby, nature establishes different mechanisms to avoid any potential locks-in, and thus evolution goes on.

On the other hand, in human environments and in particular in a specific sector such as the energy one, a niche can be the one occupied by the dominant heating system in a city or country. Technological adaptation is imposed as in natural environments by successfully implementing the most efficient technologies. In this line, technologies that are able to adapt to their environment are more likely to survive in the regime. However, human being's systems do not have natural selection and therefore instruments to make our systems to evolve must be found. Here it is where creating niches can be useful in order to promote new technologies. A new technology, over time, can break into the current regime and step by step, replacing it, giving rise to the new one to give shape to a new regime. In this body of work, a low-temperature DH represents the new technology with potential to replace the existing DH technology. Strategically managed, an emergent technology can help to succeed and occupy a consolidate position.

Spaces for test and laboratories to experiment then constitute the basis for radical innovations in order to break and/or improve the system and be made widely known within the sector they aim at. In this regard, Nordhavn in terms of energy is an energy laboratory which gives spaces and opportunities to universities, energy utilities companies and other energy actors to investigate and further test what is worth to invest in for the future. An example of a singular experiment can be the testing process resulting from a small scale implementation of low-temperature DH. Then, upscaling a successful implementation to other areas/regions will be a milestone to break the path dependence Denmark is immersed in and finally jump into an improved technology with more benefits.

- Socio-technical regime:

This is probably the most important level within the MLP framework because it is here where transitions are defined from one regime to another. It is the level where changes can have more relevance and transcendence whereas niches and landscape can be seen as "derived concepts" (Geels, 2011).

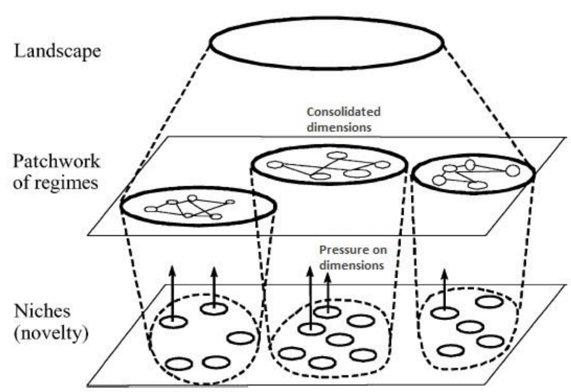


Figure 8 MLP b-Source: Inspired from Geels, 2002

The regime is the interrelation of dimensions such as markets, policy, technology and culture. All of them lay the foundation of practices, beliefs and rules which fuel socio-technical systems. Break at this point without innovation through the niche level is basically impossible. Consequently, there is a need to put pressure into these dimensions (or sub-regimes) in the regime from the niche level by deteriorating them in the direction it is wanted.

New district heating technologies (low temperature DH) can offer some advantages to future´s heating systems such as: less energy consumption with a further greenhouse gases reduction, an opportunity to integrate more renewables energies into the overall energy system and therefore a chance to phase out fossil fuels, etc. All these arguments can push regimes in multiple dimensions and at different levels with the ability of reinforcing each other, all with the intention of modifying the overall regime and make a real change on the landscape. Over time, this can be seen as a transition to a different system.

Therefore, transitions can be understood as an evolutionary process that changes slowly and step by step transforming the current regimes or as Geels states "*Evolution as 'unfolding' is included by understanding regime changes as reconfiguration processes*" (Geels, first page citing Schumpeter, 1934, p. 66) 2002).

- Landscape:

The landscape can be described as the wider context which includes demographic trends, political ideologies, societal values and macro-economic patterns (Geels, 2011). It changes slowly, and can stress the regime from the outside by creating windows of opportunity (pressures) trough developments on the landscape as it can be seen in figure 8. Kyoto protocol and other world conventions/conferences can set the rules, often with delay in action, to establish changes on the landscape with further consequences to national energy plans such as the need of reducing CO_2 levels and implementing action plans to achieve it. In this regard, advanced district heating technologies have a lot to say regarding energy goals, as in the case of Denmark, they can contribute to achieve a fossil fuel free energy system by 2050. New pressures then can influence the existing regime and settle new technological configurations into new consolidated regimes.

In summary, general tendencies on the landscape can drive a wedge between the existing regime and the innovation space where innovative technologies are eager to occupy technological niches and thus replace the old-fashioned ones. This breach, also defined as "window of opportunity", is the shuttle that a consolidated technology is waiting for, so structural changes in the regime can take place. Nevertheless, some time will be needed to witness the transition of technologies such as a lower temperature DH towards being consolidated in the regime´s dimensions (technology itself, policies, market, and culture). Furthermore, these dimensions can influence to a certain extent the breakthrough of such technology, promoted by endogenous forces and pressures within the regime, demanding the change.

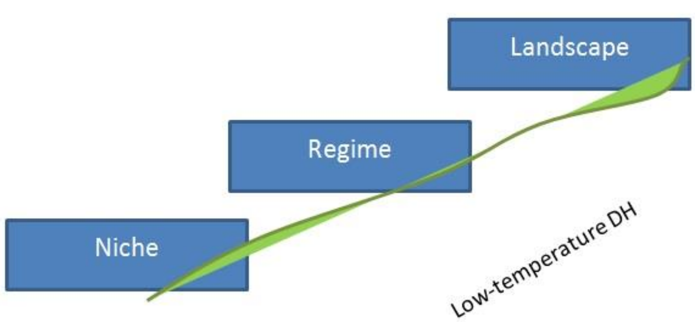


Figure 9-Low-temperature DH in the MLP

Contextualizing

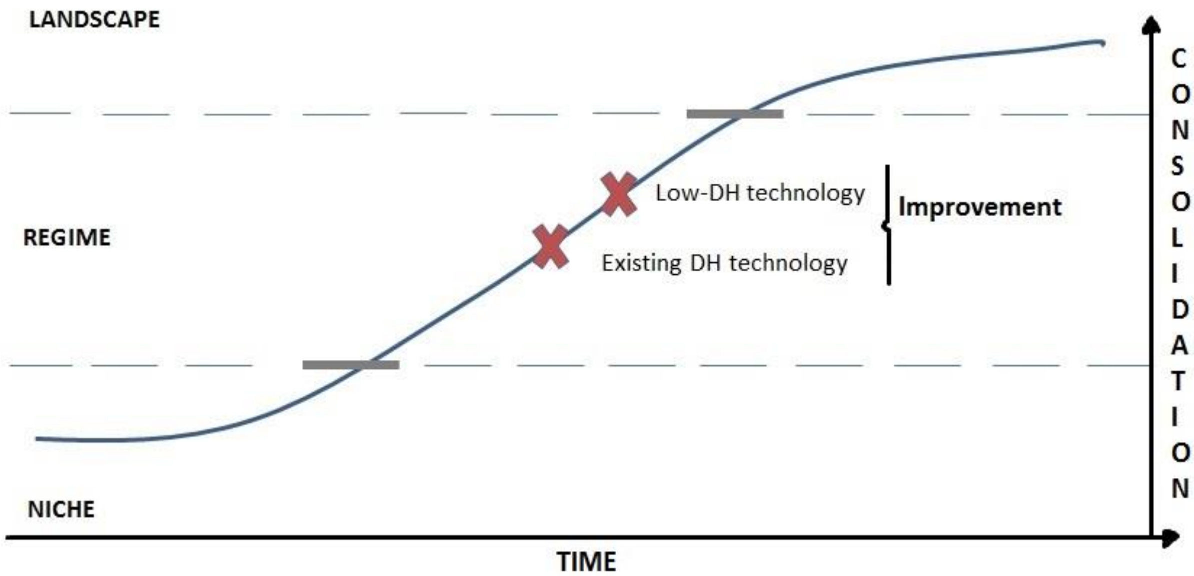


Figure 10-Depiction of Low-temperature DH trajectory in the current regime

In this conceptualisation, the technological change (a *low temperature DH technology*) does not consist of a change from one sociotechnical configuration to another. On the contrary, that entails a technological improvement on a solid and consistent regime that utilizes urban spaces, such as Nordhavn, as locations to experiment and therefore to give birth to new technological possibilities as the picture above depicts. Therefore, over time, the low-temperature DH will mature and consolidate into a more structured technology in the fossil fuel free energy system direction.

For all these reasons mentioned above, the multi-level perspective theory applies in half way since this project does not include radical transformations from one system to another by triggering them from the niche level. In fact, an incremental improvement can be found in the technology and a low-DH technology will be set in order to co-exist with the existing DH technology in the rest of Copenhagen. Co-evolution then of both technological systems must be seen before the newest replaces the obsolete one. In words of Schumpeter, (1934, p. 66) *"evolution is a process of unfolding, creating 'new combinations', resulting in paths and trajectories"*.

Geels also mentions the concept of "system innovation" (Geels 2002). It results from the interaction of several dimensions such as policies, market, culture, etc. that converge into one solid direction breaking through well-established regimes which are wanted to be replaced or improved in a common framework of landscape (macro), regime (meso) and niche (micro). In this project, a reconfiguration of elements in the district heating technology is tested by different energy engineering firms in Nordhavn. That applies for niche experimentation, but it will not be elaborated along this report.

However the new technology represents a mismatch with the *existing one* due to some configuration incompatibilities that will be discussed in further sections. In this line, the district heating trajectory is drawn which can show a possible evolution after apprehending mistakes and failures in the testing process in order to solve these incompatibilities. If the low-DH technology turns out to be an optimal heating solution then the entire energy system will slowly adapt to the new system taking into account best learnings and all the gained experience from the testing process. “When engineers and firms share similar routines, these form a technological regime and technological regimes can thus result in technological trajectories” (Geels 2002). I build upon Geels´s concept of trajectories by presenting the history of district heating in Denmark and a possible line of evolution, namely towards a lower district heating configuration in Nordhavn with subsequent upscaling process to the Copenhagen heating system. Furthermore, if it follows that trend, I pose the question of how this evolution can be understood from the regime´s dimensions defined in the multi-level´s perspective as it will be presented below.

Technological trajectories:

In the previous section, the concept of trajectories was mentioned, but not elaborated. Technical trajectories can be explained within the meso-level of the MLP, namely the regimes. Furthermore, this specific meso-level accounts for stability of existing technological development and for the occurrence of trajectories (Geels, 2002) which is why this level should be stressed. Although it is at the macro level, namely the landscape where the trajectories are more defined, regimes are much more interesting to analyze since all changes in short-time take place there and are more relevant. In other words, trajectories are born within regimes level and later, stable regimes with potential to change can result into new regimes thus altering the overall landscape. Nonetheless, the emphasis should be stressed on the analysis of technical trajectories through the study of the regime level in order to comprehend and absorb the essence of it.

It can be also argued that the emphasis on regimes highlights the enablement and constraints on new technologies (Geels, 2002). That can be very interesting to find out the benefits, challenges and other issues about the Nordhavnen case. In fact, working with the regime of district heating will bring more points to discussion than any other MLP level.

Before going further, it is of paramount importance to define the concept of trajectory:
A trajectory is the ***path*** *something or someone follows in order to achieve a goal under the action of* ***certain forces***. Thereby, a trajectory in a technical regime such district heating is the line of events that can lead to a radical innovation or to a notorious improvement as in the case of Nordhavnen. This line of events or story of the path can be linked with the path dependence´s concept due to the obvious influence history has on the trajectory a regime might follow. Path dependence refers to the causal relevance of preceding stages in a temporal sequence (Pierson 2014 citing William Sewell (1996, 262-3)). To look at the path and where it comes from (historical events) can lead to understand how current processes might develop in the near future and therefore to get closer to make reliable predictions.

Following the metaphor from Margaret Levi, 1997 cited in page 3, Pierson 2014 in which path dependence is compared with a tree that can be ascended from the ground to the top regardless how many branches break in the ascension; I will elaborate on that with a similar metaphor. In mountaineering, climbers do not always find a straight route to achieve the summit. On the contrary, they have to move backwards sometimes, to consider possible alternative routes and to make decisions that often have no point of return to the remaining optional routes. In this sense, path dependence is the result of previous choices and events that have led to the present situation and only that situation, leaving other possible trajectories behind. That regularly leads to stagnation of systems in what is commonly known in research as “lock-in”. Thereby, being aware of the multiple choices is imperative in societies if changes are wanted in order to escape from locking

the systems-in and transform the regimes. District heating then must evolve and move to a next much more efficient and more CO_2 friendly generation, so its history can continue evolving as part of its trajectory.
One important thing to take into account when talking about technical regimes is that the trajectories they follow are not only influenced by technicians, engineers or other characteristics related to the technology. In addition, users, policies, actors, researchers and financing entities shape and empower the regime and therefore its progression along time (Geels, 2002). These are the "certain forces" or pressures that might shape the trajectory´s direction. This gradual change or unfolding process that regimes experiment is inspired by subordinate elements or dimensions that work interactively as it was previously stated. For that reason, it is imperative to breakdown these components in order to achieve a better understanding.

With that said, it is possible to strip the district heating regime in its components or dimensions. The district heating regime therefore will be analysed in this report with the following chosen dimensions: DH technology, DH policies, DH market and DH culture. Not only these different dimensions are linked and co-evolve (Geels, 2002), but also they also have internal dynamics. That is why one by one they need to be explained. In fact there are two main reasons: (1) to understand them separately and (2) ensemble:

Dimensions:

Here in this section, an approach to build the District Heating regime is presented from a theoretical perspective in order to define at this time the following concepts in a broader sense. Later in this report, a more constructed and empirical analysis will provide the rest of the framework in which these dimensions interplay.

Why are these dimensions important & relevant?

The chosen dimensions are relevant to describe, define and contextualise the District Heating regime. If we want for instance to deconstruct the district heating system, then these dimensions are useful to understand it to a high degree of complexity. Technology, policies, markets and culture play a separate and interactive role at the same time that contributes to explain the on-going situation. Other elements from the regime can be easily classified into these 4 dimensions as well. For instance: financing institutions can be placed in markets while energy goals will be placed in policies or user preferences in culture. For these reasons the chosen dimensions will support an explanatory view from the regime by providing both a complementary vision of the regime and to explain why they are important in such a system.

Technology

The trajectory a particular technology such as District Heating has can be analysed to observe further developments in the regime it is being developed. Some of these developments can lead to transitions as a result of major technological transformations in the regime (Geels, 2002). In this line, technological regimes can create stability because they guide the innovative activity towards incremental improvements along trajectories (ibid); whereas external landscape developments can create problems in the regime, and then improved niche-innovations may break through, substitute the old technology, and establish a new regime. However, it is important to remind here that a reconfiguration pathway or incremental improvement is studied in this report, namely a gradual technological improvement which will contribute to modify rather than change the overall heating regime.

Picture 8-DH pipes on the left

On the other hand, niches are also important to take into account when analyzing technologies because they provide locations for learning processes, e.g. learning by doing, learning by using and learning by interacting (Geels, 2002). In this regard, the energy experimenting space known as EnergyLab in Nordhaven serves at that purpose where new technologies can mature. "*The EnergyLab is trying to find out what is wrong with the current market. In that sense, it is challenging the existing frameworks and it places in doubt the operability of today´s energy regime" (*Bøldt Jørgen, April 2015).

Another specific mechanism in the breakthrough of radical innovations could be technological add-on and hybridization. *"It means that new technologies in their early phase physically link up with established technologies, often to solve particular bottlenecks (such as CO_2 emissions)* (Geels, 2002; page 15). An example can be the shift to biomass as fuel to feed the power plants in Denmark as a result of the process of phasing out fossil-fuels. Therefore gradual changes are taking place in the District Heating technological system in Denmark in order to continue with its trajectory towards the future regime.

New or updated technologies, policies, markets, culture and user preferences can co-evolve together in order to set the final framework for the desired technology. Technological systems then are negotiated in this evolutionary process through its dimensions. Sometimes one dimension cedes and another gains. In this context, competition between different paths occurs not only in the market, but also in the institutional environment (Geels, 2007), affecting the overall regime.

Policies

It has already been discussed that technological regime shifts from a process of niche proliferation where temporary protected spaces can give birth to and for more sustainable technologies. *"These spaces in the form of technological niches could function as local breeding spaces for new technologies, in which they get a chance to develop and grow"* (Kemp 1998; page 12). However, when and to what extent policies can have an influence on these technological niches from this point? Policies can have a very notorious impact by providing initial protection as the technology is occupying more and more share in the market. Shot et al (Kemp 1998; page 12). suggest that such policies can be a mixture of three generic strategies: technology forcing, creating and using carrying networks for new technologies and strategic niche management. It can be concluded then that policies have the ability to push regime developments in specific directions. **Picture 9–Policies on the left**

Furthermore, policies set the base from which is possible to establish institutions in order to control and make the system or regime to work. In that regard, policies define the goals, objectives and targets that are to be achieved, and then institutions are in charge of safeguarding all the active elements within the policy framework. An example could be the policies to move towards less carbon-intensive energy use and public organisms such as the Danish Energy Agency, responsible for Danish building policy. Another example can be CO_2 taxes and polluter pays principle in the Danish system when seeking to promote more sustainable configurations through modifications to selection pressures in urban ecosystems (Smith, 2005).
Another point to stress about policies is the relation they keep with markets and that relates again to institutions. It can be noted that markets is one more dimension in new regimes development and there can

be an influence on the trajectory of their economies as the broader institutional framework within which those policy decisions take place (Brown et, 2008).

Markets

Markets play an important role in regimes. When a technology is being born or incubated in words of Geels, it can either emerge in a particular market or in technological niches, where they are nurtured, matured and developed. A breakthrough in mainstream markets can potentially replace existing systems and these novelties therefore can trigger disruptions and (relatively) rapid regime change (Geels et, 2006). Then if we are talking about a radical innovation, there are no established markets and no fixed preferences (Geels, 2002). On the contrary, stable regimes still experience dynamics: firms compete in markets, invest in new product development, pioneer mutations, engage in take-overs, etc. (Geels, 2007).

Contextualizing, a lower district heating technology in Denmark as it represents a gradual improvement on the regime, already has a heat market where it will be possible to further develop and continue evolving. Institutional and market transformations can often underpin transitions, the distribution of transformative power of agents, changes in respect of the transformation processes (Kemp et al, 1998).

Sometimes, regimes create negative outcomes (e.g. market failures, negative externalities, negative speculations, etc.). Nonetheless, competition can provide a common and fair playing board where every individual can access equally to the market. During the 1990s, most of the national electricity and natural gas markets were still monopolized in the European Union and the Member States decided to open these markets to competition gradually (ec.europa.eu). The liberalization of energy markets in the EU has definitely led to changes in both the landscape and regime because market competition and power struggles clearly influence the fight between incumbents and newcomers (Geels, 2007).

One disadvantage from new markets or dynamic consolidated markets is the possibility of overlapping with other markets. This can led to confusion and duplicity of roles. In this regime (DH in Denmark), it is often observed how electricity and heat sectors are interlinked and dependent one from each other. In that regard, policies are in charge of compensating possible overlaps by finding fruitful synergies across the sectors. **Picture 10-markets**

Culture

All the dimensions explained above: technology, policies, market and now culture sustain and reinforce each other at the regime level. However, culture is probably the most subjective one. For instance, technologies and markets are very similar everywhere. Even policies from different nations can have many elements in common, but culture can really change from one country to another, so much as at regional scale as well. And yet, culture is essential in technical trajectories to explain the why´s and how's.

Danish history and cultural background can help to shape policies trough institutions, leading to the development of the technology in which the market operates. Culture, nevertheless, entails user practices, people´s mind-set, education, perceptions, attitudes, etc. These components became strongly embedded in society (Geels, 2007) and can be directed at specific regimes, like the activities of the anti-nuclear movement (Smith, 2005). In the Danish case, nuclear power debate was discussed in such an exemplary way through fruitful debates as it will be seen in the empirical section. In short, debates in wider civil society serve to frame the functional reproduction and change of technical regimes (ibid).

User practices is a key component in culture due to the fact that users make up the society and thereby market tools such as special tariffs, incentives and subsidies should be focusing the customers and not the companies. For that reason, public ownership is vital in order to safeguard a good energy service as it will be seen later. On the other hand, Danish energy policy makers in particular and society in more general terms have proved that it is possible to turn a situation around and therefore change the path dependency and escaping from certain locks-in towards low carbon societies. This will be exemplified later with 1970´s Oil Crisis event.

Picture 11-nuclear debate

Transition

As it was said previously, regimes are the core of technological systems and where the real action takes place. In that sense transitions from one system to another are happening along the history of the technology concerned. A technological transition can be defined as major technological transformations in society (Geels, 2002) and thereby a gradual technological improvement can be included within this definition.

The transition is part of a technological trajectory as it takes part of the process. Therefore, understanding transitions is equally important as understanding trajectories because one can explain the other and vice versa. It has to be noticed that in this report, the transition is an incremental improvement and thereby it is conceived after all as any other changes in regimes.

In working through this issue, Smith el al, (2005) identify four different ideal types of transitions contexts:

Endogenous renewal:	Internal forces make the system to be renewed where regime change tends to be incremental as a result of perceiving pressures on the regime (Hodson, 2010)
Re-orientation of trajectories	Internal and external forces can work together in order to give a different direction to the current system (reconfiguration system´s elements)
Emergent transformations	They happen when an autonomous logic appears through uncoordinated pressures for change (ibid)
Purposive transitions	Strong degree of intention to move towards another system. Here large firms and exogenous actors are involved

Table 2-Types of transitions

As it can be noticed, a low-DH network as expected in Nordhavnen can easier be seen as an internal transition process rather than an innovative and radical transformation of the system. If we run a quick categorization with the table above, it can be observed how the low-DH network regime fits well into the fourth type of transition since the Danish Government and other Authorities pursue new heating possibilities n Nordhavn (testing site) such as the so-called technology. However, further sections will discuss to what extent this case might present elements from the other transition types.

3. Methodology

The subject chosen for this study is broad and complex in parts: Identifying and analysing the dimensions of the District Heating´s regime in Denmark followed by an extensive review of them and a further presentation of a low-temperature district heating case, specifically in the Nordhavnen area.

In order to achieve it, this chapter will try to display the methods that were utilised during the whole study. Two main approaches were used along the report´s development:

- **Research methods** which include energy libraries and books, articles, site visits and also material from Ramboll, Hofor, By & Havn and Albertslund Forsyning which have extensively contributed in this report.

- **Interviews** from both consultants taking part in the development of Nordhavnen such as Ramboll or By & Havn and energy utility companies taking part in the energy laboratory which takes place there such as Hofor.

It has to be said that these above mentioned tools were mainly used to give shape to the theories framework and to build the empirical section which are the core chapters of the report. Nevertheless, only the research methods were applied to construct the theoretical frame whereas both research methods and interviews were employed for the empirical part (please see figure 11 below).

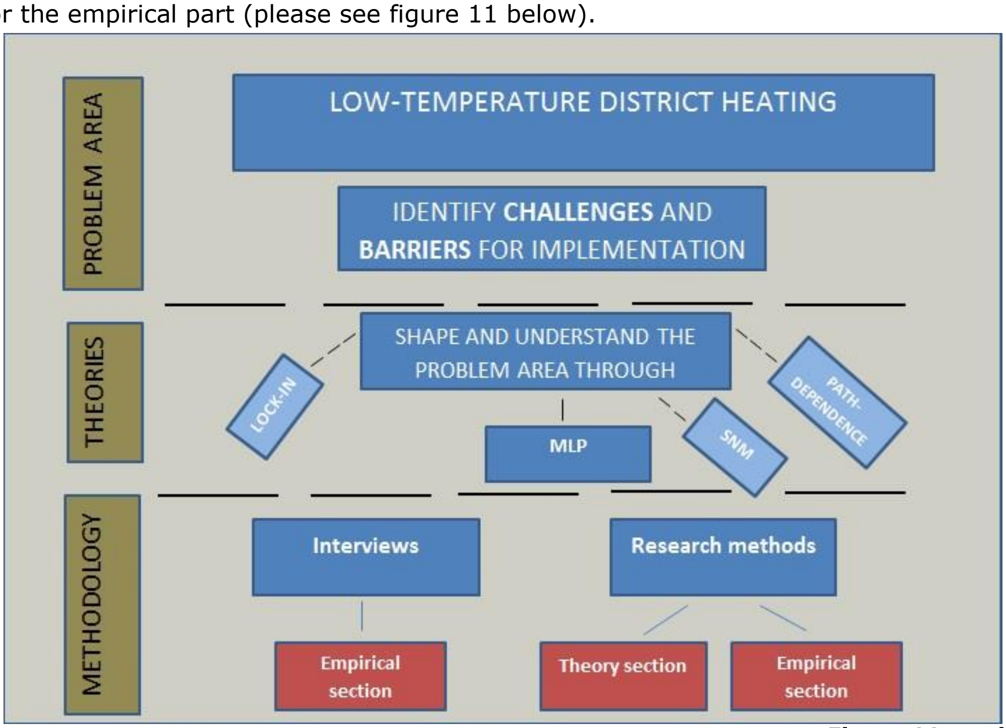


Figure 11-methods utilization

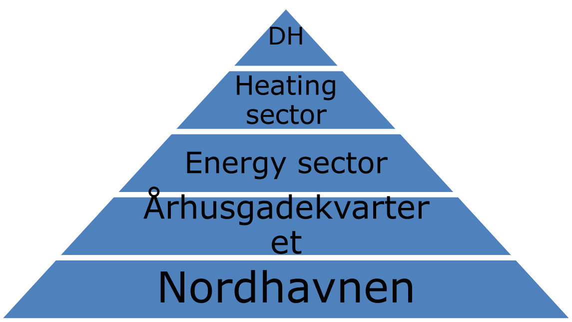
Before describing both the research methods and the interviews, it was found convenient to explain the working process during the report in order to understand the importance of networking, resulting in the final choice of informants.

Working process

Picture 12-Nordhavnen, Århusgadekvarteret

Choosing the right focus was a challenging process since the very beginning. By working at Ramboll, the Nordhavnen project landed at my feet 4 months ago and the whole Master´s thesis journey began.

As a departure point, the forecasted sustainable urban area of Århusgadekvarteret was taken. Århusgadekvarteret is a district located in Nordhavnen and was the starting point for the sale of land in the area (Ledgaard Kirsten, February 2015). It is also known as "inner Nordhavnen" and is formed by: Redmollen, Sandkaj, Nordbassinet, comprising 34 hectares in total as it can be seen in the red dot in picture 10 on the left



From an urban planning perspective regarding Århusgadekvarteret, it was decided to move forward into the energy sector and the main energy concerns for a new urban area. Due to the vast field of energy, the focus was reduced to the heating sector and from there to the district heating sector in particular as it can be seen in the pyramid on the left side (appendices I). At the same time, several articles, books about the Nordhavnen project (courtesy of Ramboll) and other material was being consulted in order to find inspiration to help in the narrowing-down process and to end up with a final problem area. After this point, with all the information gathered, it became relevant to utilize interviews due to all the resources and network of people within my reach because of my part-time job at Ramboll.

igure 12-narrowing down the focus on the left side

Choice of informants

Ramboll is one of the consultancy companies that are involved in the urban development project of Nordhavnen. Therefore, it was a good point of departure where to start collecting information by approaching different people. Networking at Ramboll was easy to carry out. However, the more contacts one gets, the more likely it is to find dead ends or to find more interesting topics that can lead to confusion thorough the working process. In that sense, the first step at Ramboll was to find out how much information about the "*Master Plan for the district of Nordhavnen*" was there. The project itself (appendices II) deals with urban infrastructure, water-works, energy supply, waste management and assessments of solar and wind loads (Ramboll, 2015). As it can be seen Nordhavnen is a multidisciplinary project that goes across different departments that at the same time provides different consultancy services. Therefore, establishing a good network of contacts was imperative to find the most relevant people for the aim of this body of work. From this point Frank Hallig, Martin Abrahamsen and Inger Anette Søndergaard from the company were contacted in order to gain more knowledge and information about the Nordhvanen project through very useful material.

From here, Frank Hallig put me in touch with Kirsten Ledgaard (appendices III) from By & Havn (current public company in charge of the Nordhavnen urban development project). That can be considered the first real interview once the topic was decided and settled. It took place at the By & Havn offices in København K on mid February 2015.

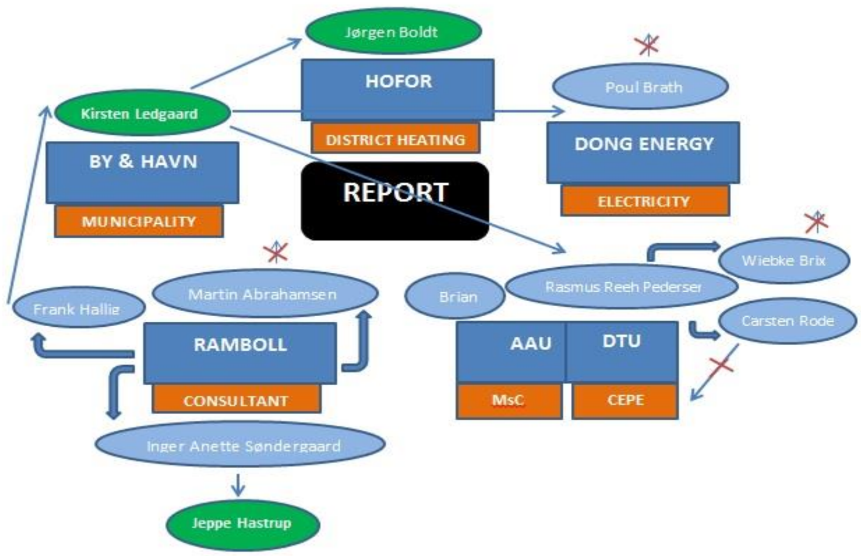


Figure 13-the network process

The way to read the figure 13 above is the following one:
First, it is better to look at the dark blue box. These ones are the main stakeholders from the Nordhavnen project concerning the report while the orange boxes only give short information about these stakeholders. Then it is possible to find the light blue ribbons which are the contacts which can be from any stakeholder. As it was said, Ramboll was set as the point of departure.

There are two different types of arrows. The thick one is used in order to link the stakeholders (dark blue boxes) with contacts "in-house" which means with contacts at the same company. On the other hand, the thin arrow serves to depict the links across stakeholders and therefore to other companies.
And last, the green ribbon shows the three main contacts that finally were interviewed while the crossed out arrow means dead ends.

Legend from the Figure 13 of the network process

Kirsten Ledgaard (Chefkonsulent) since she saw the report´s idea was switching more into energy rather than into urban planning matters, facilitated new contacts (involved in the project of Nordhavnen) in that regard. Jørgen Boldt from Hofor, Poul Brath from DONG energy and Rasmus Reeh Pedersen from DTU (CEE) were then the next ones to be approached. At that time, only Hofor´s e-mail relationship was fruitful enough for an interview which took place at Hofor´s headquarters on Bella Center, Copenhagen on April 2015. In the meantime, the networking process at Ramboll continued and gave results by finding Jeppe Hastrup through Inger Anette Søndergaard. Jeppe is the head of Department of the district heating department at Ramboll and a meeting with him was hold in mid-March at Ramboll´s headquarters in Ørestad, Copenhagen with very interesting outputs. It can be seen that between Kirsten and Jørgen interviews there is 2 months' time which was due to some problems to meet from both sides (vacations, health issues, etc.).

This process of networking can be compared with Hercules and the Hydra. In the second labour of Hercules, he was ordered to kill the Hydra from the murky waters which was terrorizing the countryside in Lerna. The monster had many heads and as soon as he smashed one head, two more would burst forth in its place. My analogy is built on the concept of that networking sometimes feels as finding blind alleys or wrong paths. Or simply, in other cases one single contact was leading to two more and so on, but in the procedure some contacts were "lost". One example of this is the failed networks with DONG Energy and DTU. In addition to that, cooperation was superficially tried with Aalborg University (AAU) with Brian Mathiesen (one of the main energy articles authors that were consulted for the report). However, due to calendar incompatibilities, it was difficult to organize a meeting and at the end it was not possible. On the other hand, DTU was very interesting and important to have its voice in this report due to the fact that is the leading institution in the energy laboratory in Nordhavnen. Unfortunately, a synergy here was neither achieved, although several contacts were approached from different networks as it can be seen in the figure 13 above.
To sum up, three interviews were finally conducted:

- Kirsten Ledgaard (By & Havn): It was the first meeting and the project was still in its very early stage. Århusgadekvarteret was mainly discussed and the interview was oriented to keep with the searching process in order to find the right people about energy-related topics.

- Jeppe Hastrup (Ramboll): During this interview, a clear picture of the District Heating framework was gained. Important material was collected for further analysis as well.

- Jørgen Boldt (Hofor): As relevant as the previous one, the meeting with Hofor provided a more defined screenshot of a low temperature district heating (LTDH) system, including problems and challenges.

Contacts			
Name	**Company**	**Interview period**	**Output**
Kirsten Ledgaard	By & Havn	Mid-February	General perspective
Jeppe Hastrup	Ramboll	March	District heating understanding
Jørgen Boldt	Hofor	April	Challenges & problems
Christian Oxenvad	Albertslund Forsyning	Mid-May	LTDH example

Table 3-Informants

It can be noticed that a fourth interview took place recently (light grey box above in the table). A late but very relevant interviewee was identified (through one of the energy books consulted) in the small municipality of Albertslund, Copenhagen. It will give a good view of what a LTDH is as it will be found on the empirical section. Due to the time period, in which this interview with Christian Oxenvad & Wisam El-khatib took place, to a large extent it supplements, corroborates and validates the results. In this line, the identification of challenges and barriers, resulting from the implementation of an on-going LTDH in Albertslund provides an efficient manner to validate the main outputs of this report. It can be concluded then that the whole interview process was in order to develop a method to narrow down and arrive to the problem area. From the most general landscape of the Nordhavnen project and district heating to a very precise case in very small scale as it is the case in Albertslund.

Research methods

Review of literature

An extensive review of literature was examined in order to develop both the theoretical framework and the empirical section of this report. The search of literature process was mainly influenced by the degree of focus achieved during the working process (see above figure 12, the pyramid). In that sense, at the beginning of the process urban strategies from Nordhavnen and local planning material was consulted.

Later, the energy field started to become relevant and several energy transition articles were searched through different tools such as google scholar. Some key words such as "*efficient energy systems*", *sustainable energy systems* and *low-temperature district heating*" were used in order to find specific reports and energy studies. It has to be said that the process of searching literature always followed the same system. In that regard, when an article was found relevant, then the bibliography related was consulted to continue with more literature in that study field. At the end and once that the scope of the project was defined, namely into district heating networks and more specifically into its latest and most updated version, the literature phase came to an end. Nevertheless, the search of literature provided good quality of information and it was revised over and over during the development of this body of work. In conclusion, a state of the art review of literature was conducted in this report with the purpose of reaching a good understanding of the energy field in general, and the district heating sector more in particular. Read the appendices IV for further information about the types of reports and articles.

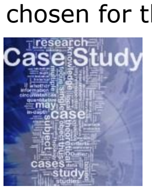
With this said, the review of literature that was conducted, illustrates that several studies agree on moving into more develop district heating technologies and on the other hand, they provide a perfect understanding about technological trajectories, transitions and technical regimes. Following this, the review of literature was mainly divided in two directions:

- Multi-Level perspective with Geels as the epicentre of the revised literature.
- Sustainable energy and district heating with researchers such as Lund, Mathiesen, etc. to help building the empirical section.

In addition, the literature review has uncovered ample published data regarding Denmark and its existing energy environment and policy which was very relevant to construct the regime´s dimensions.

Case study

From 2009 to late 2011, a pioneer project entitled Master Plan for the district of Nordhavnen was managed by Ramboll. Ramboll was responsible for all technical disciplines, including planning of infrastructure (roads, footpaths and underground), water supply works (canals and wharves), *energy*, waste management, as well as assessments of solar and wind loads (Ramboll, 2015). This multidisciplinary project which has been chosen for the purposes of this study, can illustrate very well how transitions can take shape.



Picture 13-Case study

The case study is a research strategy and focuses on understanding the dynamics present within single settings (Eisenhardt, 1988). A case study typically combines data collection methods such as archives, interviews, questionnaires, and observations. The evidence may be qualitative (e.g., words), quantitative (e.g.. 534 numbers), or both (Ibid). Thus, a case study is the right way to approach this data collection mentioned above because it allows deconstructing the components of the projects in several research directions and in that way a holistic view can be achieved.

Nordhavnen as a case study is interesting to select as it is undergoing the transition of the current district heating technology towards a LTDH. There is current detailed published data available on this process and on how the future DH system will operate. This new urban ecosystem of Nordhavnen area represents an excellent opportunity to demonstrate how energy experiments can be successfully implemented and further up scaled in the near future.

This case study will be used to illustrate:

- The benefits of implementing a LTDH
- The processes and technologies that can be applied in such a system
- To understand the low temperature district heating system and main characteristics
- How a LTDH can play an important role while moving to a fossil fuels free system in Denmark (2050) and to contribute to achieve the goal of transforming the heating sector into a totally renewable system by 2035

<u>Quality of the data</u>

The data that was obtained from both the interviews and research methods was mainly qualitative which means that is more descriptive than quantitative data. Qualitative data is useful to understand details and the context in a more panoramic point of view while quantitative data focuses more on measurable information such as numbers, diagrams, figures etc. Since the aim of this report is to comprehend the regime of district heating through the deconstruction of the dimensions that make it up, then, to obtain qualitative data from the interviews becomes much more relevant for this study.

Picture 14-Data

Nonetheless, it is important to be aware that some interviewees in order to answer the challenges and barriers of implementing a LTDH, they provided figures and other quantitative information. In that regard, quantitative is also important to consider regarding data collection in this report, but it has not the same relevance as the collection of qualitative data.
It is important to remember that the data obtained from the research methods, namely, articles, libraries provided very helpful information from a qualitative point of view as well. All contributed to build the district heating´s regime and Nordhavnen case. For that reason, a substantial review of literature was conducted (appendices IV).

Site visits

Observing in first person the area where Nordhavnen will take place gave the author of this body of work the opportunity to experience the landfilling processes and magnitude of the so called project. Unfortunately, it was not possible to see any activity related with the energy laboratory led by DTU, at least in first hand. Nevertheless, observations at the site allowed the author to witness an urban area in its early stages before being developed both in the urban scale and the heating sector.
A couple of visits were therefore made at the beginning of the development of the project with the purpose of achieving inspiration and a target to move to.

Interviews

The interview is a useful tool to elicit information from another person (Longhurst, 2003). By interviewing people relevant to the topic, important knowledge can be gained about a particular subject such as the district heating regime in Denmark.

There are many different manners to interview and several interview methods can be applied. However, in all of them a personal influence from the interviewer always makes unique and more personalized each interview. That makes interviews often subjective when replication is wanted, and at the end guidelines to structure the questions are the common denominator for all interviews.

Types of interviews applied in the study

In first place, "*Informal Conversational Interview*" (ICI) can be found as a very simple way of interviewing. Basically, all the conversation flows spontaneously with a defined topic to begin with. ICI relies entirely on the *spontaneous generation of questions in a natural interaction and typically one that occurs as part of ongoing participant observation fieldwork and the influences comes from* "what one is witnessing or experiencing at a particular moment" (Turner, 2010;p.2 citing Gall, Gall, and Borg (2003)).

The first interview with By & Havn was an informal interview (appendices III) due to the fact that it was conducted in very open and explorative manner. During the interview, interaction with the interviewee was essential to guide the process (Ibid) and by creating a good ambiance, three more contacts were obtained as it has been seen above in figure 13. These new contacts were three new chances to find more fruitful pathways in the working process. An advantage of this method is that it is much more mouldable than other interview methods and the questions can be adapted to each situation. In that sense, ICI gives more flexibility to the conversation.

The second interview with Ramboll had a more defined structure. At this point of the report, there was already a focus on the district heating sector and thereby enough background information to design several questions. As done in the previous interview, an e-mail with more elaborated topics than in the previous interview was sent in order to give the interviewee an idea about which topics to talk about (appendices V). The interview was also very informal, and was difficult to follow the pace of the small questionnaire which was being used to guide the conversation. Instead, an easy and relax way of chatting took place.

Nevertheless, important considerations about the technical configuration of the district heating system in Copenhagen were gained which will be presented in further sections.

The third interview with Hofor was much more structured. It can be said, that learning by doing process was being developed and each new interview was becoming more precise and focused than the previous one. However, the different outputs from each interview were aligned with the trajectory of the report´s structure at each time. In that sense when there was a focus on Århusgadekvarteret which now is a very general context for the report, the correspondent interview was focused on a more general structural level as well. Later on, the focus moved to an inner level, namely, to the district heating sector and the interview with Ramboll went into a more defined interview. It is exactly the same process as it can be seen above in the figure 12. And now, in the third interview, the problems and challenges of a LTDH are identified at the same time when the structure for the interview has improved. To sum up, the interviews and the degree of focus in the project have developed hand by hand and as long as more focus was achieved, more structured interviews were accomplished.

The interview guideline with Hofor can be seen in the appendices VI as well and as it was stated before, it was the result of an iterative process and learning by doing from the previous experiences.

Despite the fact of all these learnings and good conditions, the interview with Hofor was not performed as expected. It was found challenging the keep the pace of the questions one more time and the conversation suddenly was shifting from one topic to another within the district heating field. Nonetheless, the results obtained were very promising.

According to Turner (2010), citing McNamara, 2008 the "*guide approach*" adapts the designed and already structured questions to the environment. This way provides more focus than the conversational approach (ICI), but *still allows a degree of freedom and adaptability in getting information from the interviewee* (Turner, 2010; p.2 citing McNamara, 2008 (2003)). This applies for a semi-structured interview in which the questions are predetermined, but the interview unfolds in a conversational manner leading to explore other issues according to intuition (Longhurst, 2003).

The fourth interview with Albertslund Forsyning was very relevant to exemplify a LTDH case in small scale. Moving into a step forward regarding the LTDH framework, this pioneering project shows an on-going application of the system and main challenges and barriers can be validated compared with the Nordhavnen case. The interview was conducted in a very simple manner and very little material was given to the interviewees. In this case, a large part of the understanding of district heating networks in general and LTDH in particular was already achieved due to the time period in which this interview took place. Therefore, this interview was used to find out complementary details for the other interviews as well as to validate the results obtained beforehand.

<u>Transcription</u>

The transcription of data was done first from the interviewees to a notebook and from it to rewrite it into the computer divided into the most important points of each interview, while it was still recent. From there, as soon as it was becoming relevant, the different points were included according to the story line of the report, which often were overlapped.

Self-criticism

Retrospectively, there are some approaches that could have been taken in a different way such as:

More emphasis should have been placed to insist on networking with the "lost contacts" because it could have contributed with more and better insight of the district heating regime and understanding. In addition, to record the interviews can benefit in further opportunities because that would allow the author to avoid any potential confusions. Furthermore, an interview with an energy planner would have been very appropriate because it could have given a complementary perspective to the report. As well, the Albertslund case was found quite late in the development of this body of work and thereby poor reflection was done about it. And last, but not least, regardless the number of contacts who were addressed in first place (figure 13), the number of interviews was low compare to other reports of a similar nature.

As in path dependence processes, there is one single pathway that defines the present and locks the current situation. However best learning for potential opportunities can help to be aware of constraints and barriers in that regard, so dependence of the choices taken in the past can partially be avoided.

The analysis which follows will build upon the body of research conducted in these related fields to date, and reviewed above, combined with a case study illustrating the reality of District Heating technologies and its regime in order to address this gap in the literature.

4. DANISH DISTRICT HEATING REGIME

An empirical view

Dimensions are helpful to explain the regime of District Heating´s trajectory in Denmark and more specifically in Copenhagen where in the case of Nordhaven a Low Temperature District Heating system (LTDH) will be used to illustrate the case of a niche development. As it was explained in the theories chapter, technology, policies, markets and culture were chosen as the four dimensions that will contribute to describe, define and give shape to the regime´s contextualization.

Before getting into the analysis of the dimensions, it was found relevant to introduce the different territories that are used during the empirical section, here in this chapter, to provide a framework to understand the regime of District Heating. These scales are: Denmark, Copenhagen and Nordhavnen as explained before and all of them contribute to explain the regime.

Denmark

Picture 15-Denmark

Denmark is a Scandinavian country situated in the north of Europe with a population of 5.6 million people (2012). Denmark itself totals an area of 43,098 km2 with a resulting population density of 126.4 people per km2 (Denmark.dk, 2013). The capital city is Copenhagen with a population of 1.2 million as of 2012. Denmark became a member of the European Union in 1973 but remains outside the Eurozone.

As can be seen from the figure on the left, Denmark consists of numerous islands, of which there are 400, and which Fyn and Zealand are the largest. Jutland is the largest landmass to the west of Fyn and Zealand and is connected to Germany and main land Europe (McCormack, 2013).

Copenhagen

Copenhagen is the capital and most populated city of Denmark. Today it faces important demographic and energy challenges. However, in the past decades there have been a number of initiatives focusing on new technologies supporting the city's goal to be carbon-neutral by 2025 or the project of Nordhavnen.

Picture 16-Copenhagen in Denmark

Nordhavnen

Conceived as the sustainable district of Copenhagen in the future, Nordhavnen (North harbour) is being developed to accommodate an important share of its future population. Energy discoveries are taking place there right now in order to find out new efficient technologies to make Copenhagen become fossil fuels free by 2050.

Picture 17-Nordhavnen in Copenhagen

The composition of this section follows a vertical structure. The dimension of technology then provides a first introduction of the district heating regime while at the same time; the remaining dimensions (policies, market and culture) complement this explanatory view. In every dimension, a small background section can be found to provide a first overview, followed by the dimension itself as the core description of how that particular dimension contributes to understand the overall regime. Besides, every dimension provides a small section at the end, called "key findings" which summarizes the core aspects from each particular dimension.

As per the figure 14 below, it can be seen how technology dominates the regime description and the rest of dimensions contribute to and supplement it.

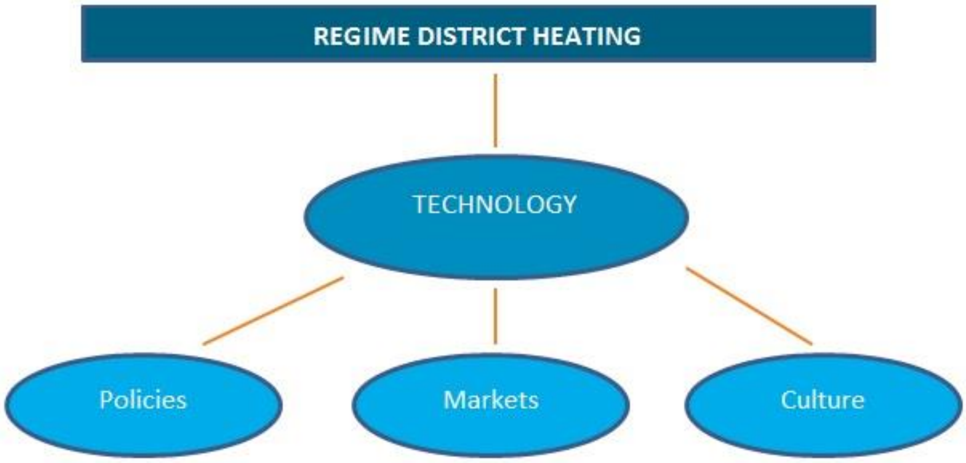


Figure 14-Explanatory description of the district heating regime

If the process is reverted, then policies, markets and culture contribute, complement and help to define the technology (DH) which sustains the description of the district heating regime in Denmark.

Technology

Technology background

The technology of district heating has been developed through a number of stages and different configurations. In the following paragraphs all these steps will be broken down to better understand the DH regime. The story line is followed throughout the main historical events.

Technological generations of District heating

Researchers such as Lund (2014), Mathiesen (2014), etc. state that the existing district heating system must be changed radically towards lower temperature district heating networks, identifying buildings (smart energy buildings) as key pieces of the smart energy systems. In order to achieve so, societies must jump into the latest district heating technology, the so called 4th Generation of District Heating (4GDH) according to many experts in the matter (Werner, Söderhol, etc.). In conclusion, it can offer the many opportunities societies are waiting for in order to achieve fossil fuel–free energy systems.

In Denmark where there is a long tradition for this technology, four generations of District Heating can thus be found: the 1st and the 2nd technological generations (1930-1970) focused on obsolete system components such as: steam instead of water as heat carrier and pressurized hot water including large heat losses in the first and the second generation respectively. However, the third generation (1970-1980) was an extension of the second focusing on combine heat and power plants and a lower temperature range than the previous one. This latest version of DH technology is the dominant one nowadays, but it leaves room for improvement toward lower temperatures (Lund et, 2014).

	Generations of District Heating			
	1	**2**	**3**	**4**
Period	(1880-1930)	(1930-1980)	(1980-2020)	(2020-2050)
Heat carrier	Steam	Hot water (≥ 100°C)	Hot water (≤ 100°C)	LT 30-70° C
Circulation systems	Steam pressure	Central pumps	Central pumps	Central & Decentralised pumps

Table 4-generations of district heating-Source: Inspired from Lund et, 2014

This historical review is needed to understand the evolution and therefore the trajectory of the district heating technology in Denmark. Further sections will illustrate the regime and the different processes that marked the trajectory of district heating in this country.

The inception of District Heating in Denmark

150 to 200 years ago there were no showers on every dwelling. Therefore, Danish people used to go to common showers that were heated from the heat surplus coming from the power plants of that time (Bøldt Jørgen, April 2015).

Later at the end of XIX century, waste to heat concept in Frederiksberg (an independent municipality situated in the western part of Copenhagen City) was the first milestone taken towards the development of district heating in Denmark. Municipality´s busy activity was generating an inevitable by-product in urban ecosystems – waste (organic mostly) – which forced to look for a solution due to all negative implications waste had at that time such as Cholera proliferation, dumping spaces, etc.

Therefore it was decided to follow the example of Hamburg that in 1896 developed a plant to burn waste to utilize the generated heat from it. A few years later, Frederiksberg Municipality decided to build Denmark´s first waste incineration plant, which not only produced heat but also electricity. In the shape of steam, the heat was led through tunnels and the system quickly spread into many communities in Denmark around the 1920´es (DBDH).

DH expansion from 1920´s to 1970´s

Heat supply grew steadily from in a centralized manner in the 20´es and 30´es, and gradually substations appeared in connection with the development of large adjoining housing areas. During WWII, heat boilers were incorporated to complement the lack of heat resulting from frequent blackouts. After the war, the situation normalized and the overcapacity created before the conflict gave a reason to expand the heating supply networks (DBDH).

New policies continued shaping during the 1960´s and 1970´s what it will be known as the district heating system we know today. In that regard, new materials and new considerations were taken into account to reconfigure the so-called system. District heating started to be based on a low supply temperature (up to 90°C) and to change to better insulated pipes. Besides, the low operation temperature made it possible to utilise the surplus heat from industrial enterprises, and also from waste incineration plants for solid waste (hot-water boilers) (DBDH).

Technology dimension

Until now, it is been presented a general overview of the district heating development along time to understand the context in which district heating has developed itself and evolved from scratch in Denmark. From this point, the technology dimension gets deeper and more focused on the real influence it has on the regime. As before, it follows a chronological line.

Becoming energy independent

Before 1973/4, energy consumption was high and there was little incentive for energy savings and no concern at all about reducing CO_2 emissions. When the crisis (the Guardian) hit the world, Denmark gave its national energy policy 180 degrees shift and reoriented it into a more economic and environmental direction. By that time, Denmark imported almost 100% of the fossil fuels used to provide heat. As a result following this, Denmark commenced an active array of energy policy initiatives, regulations and laws to reduce its dependence on imported oil and to ensure its security of supply (McCormack, 2013).To name a few of these policies: design of heat zones, building insulation and reduction of operating temperatures in district heating systems, etc. (DBDH).

It can be noted, that policies had a great influence on the technology dimension. It is due to the fact that policies and district heating technology are strongly interlinked and therefore it is not possible to explain the technology dimension without mentioning and describing some key policies. Both then are therefore key dimensions to establish new regimes within transitions and they need to adapt to each other in order to develop the emergent technologies such as low-temperature district heating.

Taxes to Energy Efficiency

Due to the smart use of taxes which were applied to fuels used in heat generation (state subsidies to ensure a proper use of energy), it allowed Denmark to encourage the use of environmentally friendly energy and efficient energy utilisation. During the 80´s decade, coal was eliminated from heat planning and no new coal fired plants were to be built (1985) and electric heat was permanently banned in new buildings and in areas with district heating or natural gas (1988) (McCormack, 2013).

1st Heat Law 1979 – Obligatory District Heating Connection
2nd Heat Law 1990 – CHP Conversion

In the first law at the end of the 70´s, municipalities were urged to develop heat maps to plan where heat was being used, where it was being generated and future heat demands and generation capabilities. The idea behind was to decentralize the system towards more local heat units. The second heat policy was to convert existing heat only plants to combined heat and power. At this point, it becomes relevant to introduce briefly the concept of cogeneration (McCormack, 2013).

Cogeneration: A cogeneration Plant, also called Combined Heat & Power (CHP) plant, is the simultaneous production of electricity and heat, both of which are used. Not only waste heat from thermal plants is used, but also heat from large buildings, industries, etc. It differs from a conventional plant (presented in the introduction section) in the efficiency rate as it can be seen in figure 15 below.

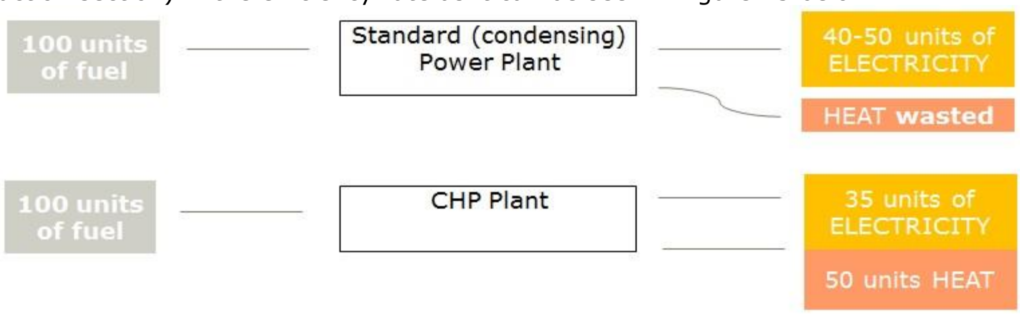


Figure 15-Comparison between a standard plant and CHP plant

As per the figure 15 above, it can be noticed that cogeneration plants (CHP plants) achieve higher rates of efficiency than conventional plants and that is why they are so important in district heating networks.

As it was said before, after the first heat law, the second heat policy was to convert existing heat only plants to combined heat and power. This was deployed in 3 phases between 1990 and 1998 (ibid).

Phase 1: Large coal-fired DH plants with access to a natural gas supply were to convert to natural gas-fired, decentralised co-generated heat and electricity plants. And, large natural gas-fired DH plants were to convert to natural gas-fired, decentralised co-generated heat and electricity (DEA).

Phase 2: Remaining coal-fired DH plants with access to natural gas supply were to convert to natural gas-fired, decentralised co-generated heat and electricity. Medium-sized natural gas-fired DH plants were to convert to natural gas-fired, decentralised co-generated heat and electricity. The majority of DH plants outside the public systems were to convert to straw, wood chips or other biofuels (DEA).

Phase 3: Smaller natural gas-fired DH plants were to convert to natural gas-fired, decentralised co-generated heat and electricity. Remaining DH plants outside the public systems were to convert to straw, wood chips or other biofuels (DEA).

The efficiency of plants' co-generated heat and electricity has risen sharply, from 50% in 1980 to approximately 70% in 2000, because increased co-generation of heat and electricity saves large amounts of fuel. And nowadays, they can reach up to 90% efficiency (Ramboll, 2015).

Restructuring subsidies structure

As a result of subsidy restructuration, it was determined that electricity was being produced unnecessarily when heat demand was high, and being sold off, sometimes at a loss. As a result in July 2003, CHP were exempted from the obligation to co-generate electricity and heat continuously in order to qualify for electricity subsidies (McCormack, 2013).

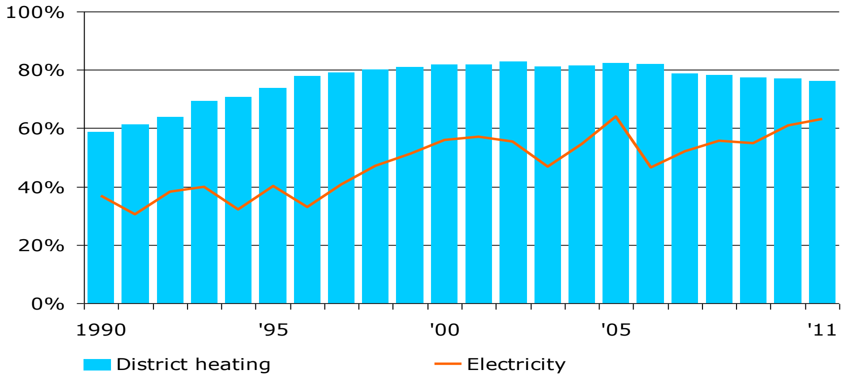


Figure 16-CHP share of thermal power and district heating production between 1990-2011-(DEA, 2012)

In figure 16 it can be observed that in the past years, a decline in large scale power production and the increase in wind turbine (and hydro power production to fill this capacity requirement). This has led to surplus of wind which calls for new technologies to take charge of it. Heat pumps combined with a low-temperature district heating might be a solution as it will be discussed in further sections. At the end, in 2003 CHP subsidies were altered, so that plants were no longer penalized for only producing heat or electricity alone.

This has resulted in more condensing mode operation of the larger plants, only producing electricity at a high efficiency in the 50 percentile range, but not in the 90 percentile range as would be the case if also producing heat. Figure 16 above indicates this change. Following the 2003 decision, it can be seen that electricity and heat production no longer trend together, with a peak in electricity production in 2005. This reflects the move of CHP plant operators to only produce electricity and heat together when there is a demand for both, and switching to condensing mode when there is only a need for electricity (McCormack, 2013).This all contribute to think and reflect about the transition that Denmark is into a more electric energy system. This will more elaborated in the discussion chapter.
One more time, it can be observed the interrelation between policies and district heating technology. This presentation of policies is needed in order to understand the history of DH over the technological generations.

Structure of District Heating

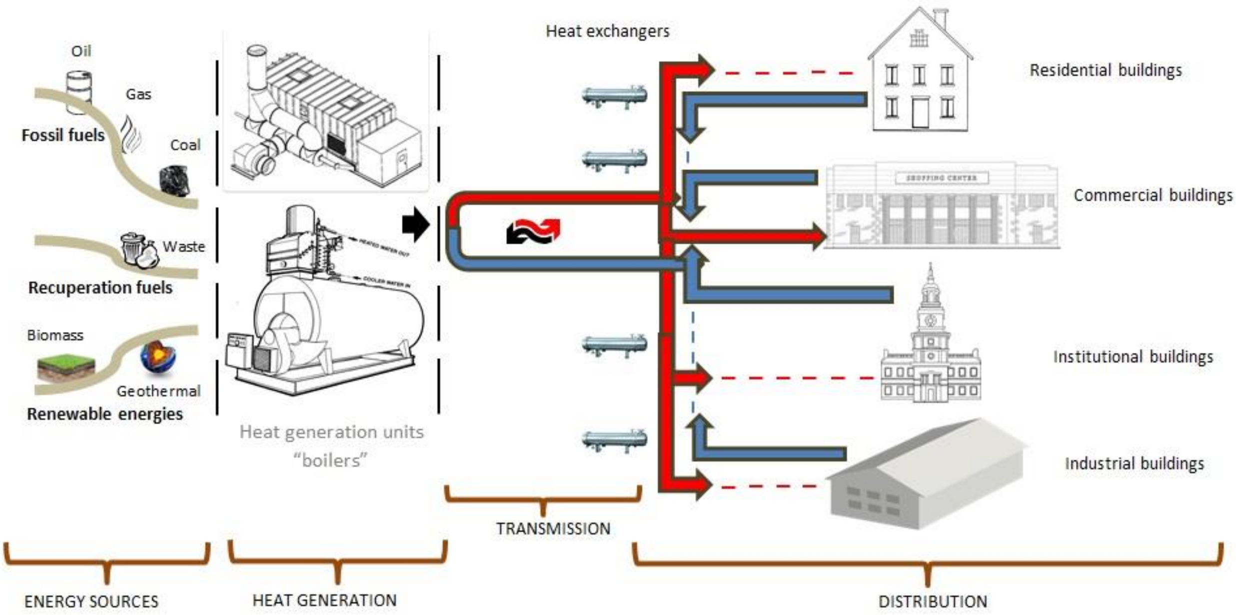


Figure 17-DH infrastructure inspired from Power solutions

To present the system today, it is easier to take a regional example. For that reason, Copenhagen has been chosen because it illustrates quite well the integration of energy systems within the city and because it is the regime that can better explain the Nordhavnen DH case, core of this report.

1. Technology infrastructure – Key components

Here the main components of a District heating technology´s infrastructure are presented in a more detailed manner compared to the introduction presentation of DH as it can be seen from the figure 17 above:

Heat generation:
Heat can be generated from a variety of sources including: recycled heat such as waste/surplus energy from power generation such as CHP, energy from waste incineration or thermal treatment, surplus heat from industry, geothermal, solar and boilers (biomass and/or fossil fuels) (Moloney, 2011).

- *Heat accumulators:*
  They are installed in order to give the system more flexibility, so they can level daily heat load variations. It has other benefits such as to serve as water storage or to optimize operation of solid fuel boilers (DBDH).

Transmission line: It primarily consists of piping. When the heat is generated from the very source, namely the power plant for instance, is transmitted to the heat exchangers which are strategically distributed across the city nearby the buildings. It is operated at higher pressure and/or temperature than the distribution network (see below) (DEA, 2014).

- *Pre-insulated pipes:*
  Pre-insulating steel pipes are covering the insulation with a water-resistant casing that was invented in Denmark in 1960. Today, pre-insulated pipes are buried directly in the ground, carried under seawater and fitted without the use of compensators or other stress releasing methods with a lifetime of at least 30 years (DBDH).

Distribution network: As in the figure 17 above, it is what connects heat exchangers with dwellings and supplies heat to residential, commercial and institutional buildings, and for industrial processes (Ramboll, 2015). It is important to not confuse it with transmission line which is what connects generated heat from the source with the heat exchangers (Hastrup Jeppe, March 2015) as previously stated.

- *Heat exchangers or substations:*
  They are used to separate circulating water between the distribution network and the transmission line. They minimise pressure loss and simultaneously maximising the heat transfer coefficient (DBDH).

- *Speed-controlled pumps:*
  To deliver the exact amount of heat needed at any given time to all consumers is quite a challenge (DBDH). Another reason for using these pumps is the reduction of heat loss from the network due to reduced temperatures outside peak hours. These peak-load boilers operate during the peak hours supplying heat according to demand. This technology is good not only as back-up, but also from an economic perspective: it is better to use decentralized peak load boilers that only work a few times a year rather than invest in insulated pipes around all the city for such little use (Hastrup Jeppe, March 2015).

End-user:

There are two types of systems: those that are generation driven and those that are demand driven. In the first systems heat is generated based on predictions and either the dwellings are too cold or too hot while in the second systems customers are able to regulate heat use according to individual needs and be invoiced according to the amount of heat delivered to the substations (Moloney, 2011). The Copenhagen case and most of the Western countries have the second approach because it is much more efficient and much more energy is saved.

- *Heat metering:*

Picture 18-heat meter

In Denmark, it is mandatory to pay for heat and other utilities like water and electricity according to consumption. All district heating installations are equipped with energy meters and heat allocators. It brings along energy savings and thus CO_2 reductions; it is the consumer´s awareness of his own consumption that motivates the consumer to consider how energy can be saved (DBDH).

<u>Main characteristics of a DH network</u>

- Maximal design temperature 95 °C
- Variable flow and operational supply temperature down to 60 °C in the summer
- Production of domestic hot water in each building substation
- Closed heating circuit and water treatment (DBDH).

Domestic hot water system

- It is important make a distinction between the heat carrier, namely water, for the DH networks and the supply of hot water. There are two different systems that use different pipe´s systems, but they have in common the exchange of temperature through water.

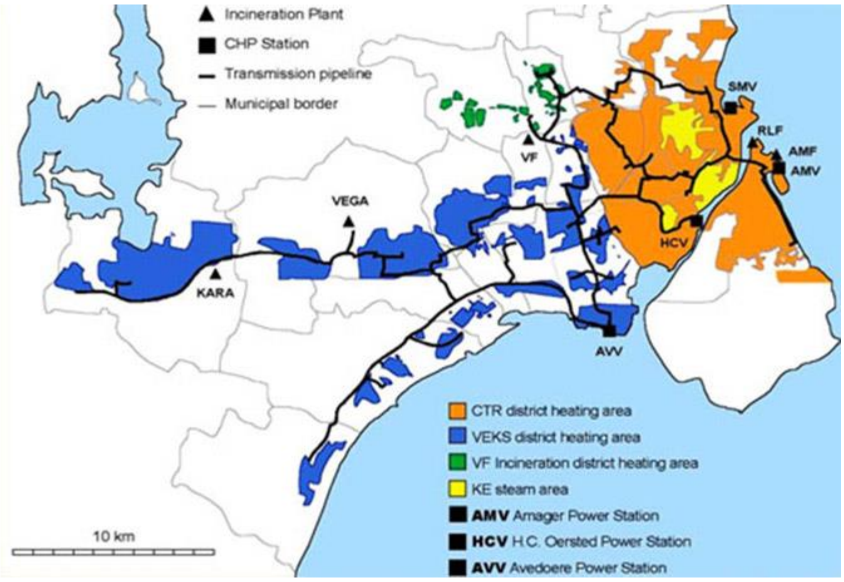
2. Main authorities

In Copenhagen, the local authorities are the central players in the public heat-supply because of the development of heating plans. They also have responsibility for expanding district heating and for implementing any changes made necessary by amendments to the regulations in the Law on Heat Supply (DEA).

On the one hand, the Danish Energy Authority is an agency under the Ministry of Climate, Energy and Building. It has established the operation of district heating in order to ensure that both cost-effectiveness and consumers' heating costs are taken into consideration.

On the other hand, the Danish Energy Regulatory Authority (DERA) and the Energy Supplies Complaint Board monitor the district-heating sector to guarantee fair prices and conditions. All district-heating and co-generation plants are obliged to keep the DERA informed about consumer prices and conditions such as tariffs and delivery conditions so that it is able to handle any complaints or objections (DEA). The Energy Supplies Complaint Board deals with private consumers' complaints regarding energy companies' purchase and delivery of heat. It was set up on 1 November 2004 (ibid).

3. Facilities



Copenhagen has 54 km network, 26 heat exchanger stations, 4 booster pump stations and 9 heat-only boiler plants (Ramboll, 2015).

The heat is supplied from 4 CHP plants, 4 waste incinerators and more than 50 peak boiler plants to more than 20 distribution networks by 3 interconnected transmission companies, CTR, VEKS and Vestforbrænding (DBDH).

Picture 19-Map of the heat transmission network supplying Greater Copenhagen, DEA

As per the picture above it can be seen:

- **CHP plants:**

  - *AMV, Amager Power Station*: Situated on Amager in Copenhagen. It produces annually 7 TWh of electricity and 7 TWh of heat – corresponding to about 17.5% of Denmark's electricity consumption and about 17% of Denmark's total district heat consumption (Danielsen, 2013). It accounts also as a geothermal plant (Ramboll, 2015).

- *HCV, H.C. Oersted Power Station*: It is a natural gas fired power station in Copenhagen.
- *AVV, Avedøvre Power Station*: is located at Avedøre Holme in the southeast corner of Hvidovre in Copenhagen and it is one of the most energy efficient power plants in the world (McCormack, 2013).
- *SMV, Svanemølleværket*: Located in Nordhavnen. Part of the modernization entailed conversion to remote control of the plants operated from H. C. Ørstedsværket.

- **Waste incinerators**:
    - *KARA*: The major part of the residual waste is treated at the company's waste-to-energy facility in Roskilde (Kara)
    - *VEGA*: Equipped as an auxiliary burners in the Copenhagen suburbs (Kleis et al, 2004)
    - *RLF*: Rensningsanlæg Lynetten treats treat sludge from approximately one million people (Ramboll, 2015).
    - *AMF*: Amager Resource center is also located in the North of Amager where Amager Bakke project is taking place (a multi-functional, social and cultural waste-to-energy plant with an emphasis on sustainability)
    - *VF*: Vestforbrænding operates Denmark's largest plant for incineration of waste.

- **Peak boiler plants:** In the description it was said that there are 50 peak boiler plants in Copenhagen that can operate quickly to supply heat in peak hours. Together with **20 distribution networks** shape the entire district heating mega network in the Danish capital.

District heating´s connection in Copenhagen

The DH goal in Copenhagen is to increase the connection to the DH network up to the point where is economically feasible to build infrastructure (pipes) and the remaining areas thus supplied by individual heating. Heat pumps are a good option for the latter areas due to its great efficiency conversion technology or natural gas boilers as it is nowadays, while large heat pumps and geothermal energy has good potential to electrify part of the core DH network. As mentioned before, this electricity transition within the Danish energy system will be further elaborated later in the report.

In Denmark, 63% are connected to district heating systems (DBDH) accounting for 50% of the total heat demand (Brand, 2013). On the other hand, in Copenhagen City today´s district heating network covers 97% of the total heating needs of the city-the equivalent of a floor area around 50 million square meters.

Low-Temperature District Heating (LTDH) concept

In order to reach a non-fossil heat supply as part of the future sustainable energy system, a state of the art district heating network can potentially play an important role in Copenhagen and thus in Denmark in a bigger scale. District heating technologies can be further developed in order to decrease grid losses, exploit synergies, and thereby increase the efficiencies of low-temperature production units in the system. LTDH is merely a concept to describe low-energy technologies and refurbished buildings (Brand, 2013). To contextualize this low-temperature idea, energy data from Denmark is presented now: In 2010, the average DH supplies (T_{sup}) and return (T_{ret}) temperatures in Denmark were:

- heating season T_{sup} 78.7°C and T_{ret} 41.4°C
- non-heating season T_{sup} 73.3°C and T_{ret} 44.1°C

LTDH accounts for new designs of space heating systems in both types of building (existing and new ones) with approximately a supply temperature of **50°C** and a return temperature of **25°C** with the option of higher temperatures during peak periods (Brand, 2013). Therefore, heat loss can be reduced because the heat loss from the DH network is proportional to the difference between the supply temperature and the temperature of the surrounding ground, so lower supply temperature means lower heat loss. According to Oxenvad Christian, May 2015, a LTDH is expected to save 70% concerning heat losses. Then, in total it can be said that approximately a 10% of the overall system will be saved which will lead to energy savings and CO_2 reductions which is crucial towards fossil fuel free energy systems.

The Danish´s goal of phasing out fossil fuels from the heating sector by 2035 is the very first argument for investing in such a technology. Secondly, the application of a LTDH system will lead to an increasing number of low-energy and refurbished buildings with reduced heat demand. And last, but not least, the heat supply of buildings were originally designed for medium supply temperatures, so it is very possible to adapt them to the new system (Ibid).

Key findings

In summary, the technology dimension provide us with a good understanding of the historical perspective from the inception of the technology to the most advanced and cutting edge generation of district heating, namely a LTDH. This section has offered an overview of the inexorably development of energy policies thus contributing to the technology development, mostly after the oil crisis in 1973 and the great influence of the heat laws which have echoed in today´s energy landscape. Besides, a smart use of taxes and subsidies allowed Danish energy system to flourish and to focus on more efficient technologies. At the end, the district heating structure was presented, with special attention to the physical infrastructure and components, actors in the system and the main facilities taking part in the district heating network in Copenhagen. Energy transitions can be better understood by breaking down the components which interplay in such processes. In this section, the technology has been described over time until reaching the 4GDH which has proved to be a suitable substitute for the current DH technology. In this description, policies have contributed across the section to better define DH evolution. However, in the next chapter, policies will be presented in a more strategic manner.

Policies

Policies are relevant to be included in the deconstruction of regimes because by tracking them it is very easy to follow the history and development of a certain technology as for instance district heating. In addition, policies set the base for institutions which also can help to apply the laws along time and to establish order and good control for a certain technology. Besides, policies regarding energy in Denmark have evolved to the point that there are specific policies for subsectors within it such as heating. The birth of heating laws is presented here by following the history in chronological order thus complementing the technology dimension due to the numerous interrelations as previously seen.

Before getting deeper into the regime regarding the policies dimension, it is imperative to provide a quick overview of the general situation where district heating was developed in terms of the different policies that had an influence on the technology. Here it can be found the development of district heating trough time throughout the main policies.

Policies background

It was told before in the technology section, the inception of heat utilization for the first time in common pools by using the heat wasted from the thermal power plants. Later, it was presented the case of the first waste to heat plant in Denmark which was placed in Frederiksberg inspired by an example in Hamburg. The system quickly spread into many communities in Denmark around the 1920´es and gradually regular district heating substations appeared in connection with the development of large adjoining housing areas.

National development policies continued shaping during the 1960´s and 1970´s what it will be known as the District Heating system we know today with new materials and new technical configurations to become and be based on a low supply temperature (up to 90°C).

Policies dimension

Oil Crisis 1970's

The modern policies of District heating in Denmark started with oil crisis in 1973/4 because the country gave its national energy policy 180 degrees shift and reoriented it into a more economic and environmental direction. Due to its fossil fuels dependency from the international markets, Denmark used this point in history to become aware of the need of good policies, regulations and laws to ensure its security of supply (McCormack, 2013) such as heat zones, building insulation and reduction of operating temperatures in district heating systems (DBDH).

1st Energy Plan (1979)

As a result, of the Oil crisis, Denmark prepared and developed the first overall energy plan in January 1976, with the subsequent establishment of the Danish Energy Authority in April of that year and a Ministry of Energy in 1979. Taxes on oil and electricity were introduced and subsidies for utilisation of surplus heat from industry were introduced, reflecting at this early stage the 'polluter pays' principle

(McCormack, 2013). After stable energy policies since 1976, municipal planning and a tradition for co-operation in the society have been important preconditions for CO_2 emission reductions in Denmark (Ramboll, 2015). Several policies were triggered as a result of both the oil crisis and the development of the first energy plan in Denmark. Some of them can be seen next:

1st Heat Law 1979 – Obligatory District Heating Connection

As it is been said previously in the technology dimension section, the first law on heat supply was introduced in 1979. Municipalities and county councils were directed to develop heat maps to plan where heat was being used, where it was being generated and future heat demands and generation capabilities. By 1982 connection to the public system started to be obligatory by law (McCormack, 2013). This was an important moment and a a key reason to explain Denmark´s success in energy policies in general and heating policies in particular.

Then the national plan for heating was saying that it should be a regional development for heating, or in other words, regional heating plans. In that way, every Kommune developed their own way to supply heat to their homes and built their own distribution network. Later, these distribution networks became part of the general transmission line through heat exchangers and all together built up the district heating network exchangers (Hastrup Jeppe, March 2015).

Heat supply act

The Heat Supply Act from 1979 empowers the Minister for Energy to ban the use electric heating in new buildings located within a district heating or natural gas supply network (IEA). After the heat supply act, natural gas was banned for the centre of Copenhagen while it was allowed in the surrounding areas of the Copenhagen region (Bøldt Jørgen, April 2015) (please see DH´s connection in Copenhagen above). This will be later reflected in the discussion section.

2nd Heat Law 1990 – CHP Conversion

The purpose of this policy was to continue with the heating planning. At this stage, the next move was to convert existing heat only plants to combined heat and power. This was deployed in phases between 1990 and 1998 as it can be appreciated in the previous dimension, and involved conversion of large to medium coal or gas fired plants to CHP, with gas as the primary fuel.

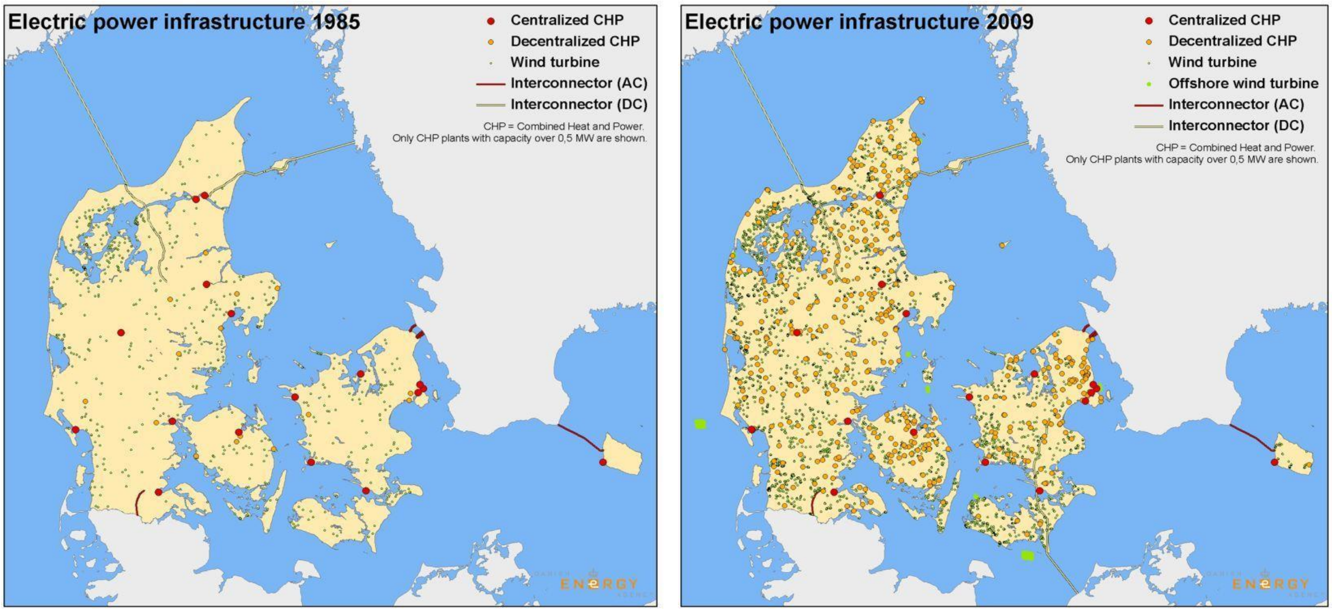
In 2001, the Danish District Heating Association published a study which showed that most District Heating is competitive with individual oil heating exchangers (Hastrup Jeppe, March 2015) and from that point connection to the DH grid grew quickly.

Subsidy Restructuring 2003: CHP Mode Operation no Longer Obligatory to Qualify

In the previous dimension, it was explained this fact from a technological and technical perspective. Here, it will be told from the policies point of view.There was an energy policy driving change in generation which determined that electricity was being produced unnecessarily when heat demand was high, and being sold off, sometimes at a loss. As a result in July 2003 CHP were exempted from the obligation to co-generate electricity and heat continuously in order to qualify for electricity subsidies. This has led to production of electricity or heat separately when there is a demand for only one and when the price is favourable (McCormack, 2013). However, after the 2003 decision, electricity and heat production no longer trend together (figure 16) which reflects the shift of CHP plant operators to only produce electricity and heat together when there is a demand for both, and switching to condensing mode when there is only a need for electricity (Ibid).

Decentralization

Decentralization was a process of transformation within the Danish energy system, as a result of the energy policies, that consisted of downscale the CHP units towards less centralized units, so heat demand can be better controlled and managed.



Picture 20-Decentralization process: comparison between 1985 and 2009 (Danish Energy Agency, 2015)

Typically, CHP plants are either centralised or decentralised. Centralised CHP are usually much larger than decentralised CHP. The former were originally electricity plants (generating only electricity), while the latter were originally heating plants (generating only heat). In Denmark, there are 16 centralised CHP which account for large cities and approximately 415 decentralised plants in smaller centres (DEA, 2015).

In picture 18 above, it is depicted the transition from a hierarchal centralised to a semi-decentralised energy system (Mathiesen, 2013) where the transformation took place along the 3 phases already presented above as a result of the second heat law in 1990. By doing so, more flexibility in the energy system was gained while at the same time more autonomy was given to municipalities and local governments.

Another example of decentralization can be the peak boiler plants which are modular units that can start operating when demand is very high and cannot be supply with the existing infrastructure. However, as peak hours are temporal, it is more convenient for the overall system to have a less efficient technology that rarely operates, rather than more CHP units working at half capacity. This approach is good not only as back-up, but also from an economic perspective: it is better to use decentralized peak load boilers that only work a few times a year rather than invest in insulated pipes around all the city for such little use (Hastrup Jeppe, March 2015).

<u>Continuous Energy Policy Development</u>

Policies have continued shaping the current energy system in Denmark and the heating sector in particular. Recently, a comprehensive agreement for the period of 2008-2011 was aimed at further reduction of Denmark’s dependence on fossil fuels, with a target of 20% renewable energy consumption in 2011 (McCormack, 2013).This represents an energy milestone for the Danish society towards more environmentally-friendly energy systems. However, more energy milestones will be seen as long as Danish policies continue evolving.

Denmark's EU 2020 Targets

Continuing with setting ambitious future energy targets, new milestones are expected to be achieved in this process which increasingly resembles to a transition to a better and less dependent energy system. Some of these targets can be found here below in table 5:

Targets
30 % renewable energy in the total energy consumption by 2020
10 % renewable energy in the transportation sector by 2020
20 % reduction by 2020 in greenhouse gas emissions (compared to 2005)

Table 5-Danish energy targets-Source: (McCormack, 2013).

Fossil-free heating and electricity sector in Denmark by 2035

The Danish government has set a number of targets for the further development of the energy sector: Eliminating coal completely from power generation by 2030 thus covering Denmark´s electricity and heat supply by renewable energy by 2035 (ENS, Danish energy model, DEA). This will have a positive impact to incentivize new efficient and green technologies to emerge and become part of the current energy regime.

Denmark´s goal to be fossil fuel free by 2050

And last, in March 2012 a historic new Energy Agreement was reached in Denmark. The Agreement contained a wide range of ambitious initiatives to bring Denmark closer to getting rid of any type of fossil fuels to supply the energy sector (electricity, heating & transport sectors) by 2050 (DEA). This point implies the end of the energy horizon in this report, but also for Danish energy planners so far in Denmark. However, very much has to be done from today till 2050.

Key findings

In summary, it is been observed the passing of policies starting with the Oil crisis. Due to a firm energy policy and cooperation between central and local authorities, heats supplying companies and private companies, considerable results have been achieved in Denmark during the last 40 years since the energy crisis (DBDH). For that reason, Denmark has been for decades, the world leader in the development and implementation of innovative technologies related to DH as result of the decision taken through its history, including important energy targets and decentralization processes. All the presented policies have helped to shape the trajectory of district heating technologies towards a more efficient and less polluting regime.

Market

The market is interesting to analyse since the economic perspective is always mandatory to take into account when dealing with technologies and how they developed from the very beginning. Therefore, here the market section will complement again the technology dimension. The market appears as a way to maximize benefits and to look for the most efficient manner to both make technologies work and to consolidate them into a system or a regime. "Markets can select the radical innovations with potential to success in subsequent application domains or market niches" (Geels, 2002). Once that the market is established and adapted to an specific technology (heat market), it is easier to maintain it through the use of market tools such as policies, taxes, subsidies, competitors, etc. It will all contribute to develop it in order to achieve better management, better quality services and higher efficiencies in the system.

It is important to take into account that the energy market in Denmark is very extensive. Even the heat market comprises quite considerations concerning the district heating technology. Nevertheless, an attempt to summarize a brief picture of the district heating market is presented below.

Market background

This first section shows how market and economy have influenced the development of district heating in different policies stages. The next section will show in a descriptive manner its background. As it has been seen when describing the district heating policies' section along the historical line, there were several plans that helped to make up what district heating is today. Some of these plans, where economy played a very important role to the development of district heating trajectory, are presented next.

It was seen that policies in the 1960´s and 1970´s made possible to adapt the new technological innovations to each generation of district heating which allowed to great economical savings. For instance the materials utilised to reduce heat losses or lowering the supply temperature (up to 90°C). It all contributed to make the distribution network cheaper and more competitive compared with individual heating. In line with this, later the first most important policy was the 1st energy plan which came in 1976.

Self-sufficient energy system

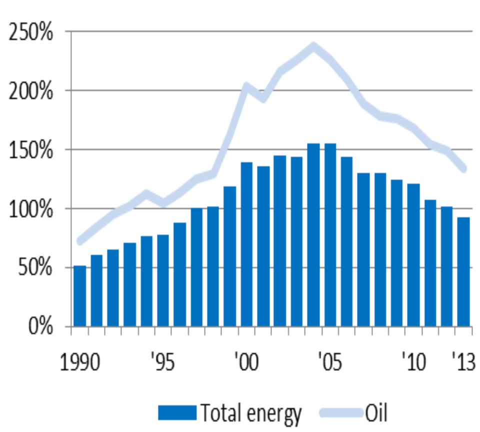


Figure 18-Degree of self-sufficiency Source: DEA

In Denmark, cheap oil was fuelling about 90% of the electricity production in the years before the oil crisis, making the country especially vulnerable to the jump in oil price (Meyer, 2004). In order to become independent of international market fluctuations as a result of the volatility of fossil fuel prices, Denmark designed a plan to strengthen its energy security. That, at the same time gave room to new clean technologies such as more share of wind power. In figure 18, it can be observed the degree of self-sufficiency obtained by Denmark as a result from the policies adopted in the years after the crisis. The production of hydrocarbons in the North Sea has contributed to transform Denmark into a self-sufficient system regarding energy since 1997.

Introduction of taxes

Oil & Electricity Taxes Introduced

The importance of taxes on oil is due to the fact that energy savings were incentivized when oil prices were low because taxes were being applied. In that way, it was possible from the Government level to invest in renewable technologies with all the money saved while other countries did not take that approach.

The vulnerability to supply shocks and oil price fluctuations was evident, and the first oil crisis in 1973 demonstrated the importance of the energy sector for Danish society and the need for a comprehensive energy policy (Statensned). Nevertheless, a smart use of taxes during the 1970s and 1980s allowed the use of environmentally friendly energy and efficient energy utilisation by applying these taxes to fuels used in heat generation. An example is biomass and biogas which were exempted from taxes due to its renewable nature (Bøldt Jørgen, April 2015).

Environmental Taxes Introduced 1992 & greening of trade and Industry 1995

A CO_2 tax was introduced in 1992 to cover energy savings in industry, decentralized CHP, utilization of biofuels, electricity production and the completion of the district heating network. This package was designed in such a way that the additional taxes on trades and industries were transferred back through tax reductions, subsidies etc., with the goal of maintaining the existing cost base of trade and industry (McCormack, 2013).
This momentum of providing different mechanisms for redistribution of monies from emissions and energy taxes to support the greening of trade and industry was continued until 1995 with a new tax package. In fact, these methods allowed retransferring monies back to industry to reduce the burden and impact of these new taxes on industry (DEA, 2000).

As it is been discussed above, taxes have been in place on electricity and oil since the 1970’s in Denmark, with subsequent taxes placed on natural gas and coal. However fuels for electricity production are today exempted from the taxes, as taxes on these fuels would have a negative influence on Denmark’s large import and export of electricity. Instead, electricity that is produced has an energy tax (McCormack, 2013).

Picture 21-tax

Continued Economic Growth

Although this history of energy policy since the late 1970s in Denmark has seen significant change in order to incentivise certain energy forms and dis-incentivise others, it has not affected its economy. From 1980 to 2010, the Danish economy has grown by 78% while energy consumption has remained almost unchanged (DEA, 2010) in tandem with CO_2 emissions reducing by more than 13% (Energy Styrelsen, 2009) (McCormack, 2013).

Market dimension

The next part will show in detail, the structure and main characteristics of the district heating market and other aspects involved from a descriptive point of view. It will all contribute to obtain both a full picture of the DH regime and a better understanding about how markets influence energy transitions.

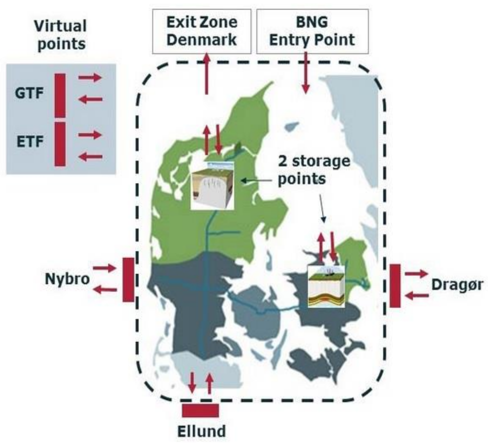
The Danish Heat market

The Danish heat market is part of the whole Danish energy market which comprises both heating and electricity. Although these two markets are traded separately, their productions are interlinked in some generation industries due to the prolific volume of combined heat and power plants throughout the country (McCormack, 2013).

The heating market is guided by the state heat laws. The municipalities in each district are the main authorities regarding district heating, and regulate the market in each district according to the state heat laws which are summarized here from the policies dimension section: 1st Heat Law 1979 – Obligatory District Heating Connection; Heat supply act & 2nd Heat Law 1990–CHP Conversion.

The district heating companies in Denmark are owned either by the municipalities (particularly in the major cities), or by local consumer co-operatives or foundations. Regarding the electricity, the regional power companies are owners of the two power pools, ELSAM in Western and ELKRAFT in Eastern Denmark. ELSAM and ELKRAFT are in charge of overall power planning and load dispatch and operate their respective independent transmission networks as well as the international power interconnections to Norway, Sweden and Germany (Ibid).

<u>The Danish gas market</u>



Within the heat market, the Danish gas market can be found which as well is fully liberalised, and all consumers are free to choose their gas supplier. The system consists of a transmission grid and distribution grids on land and of marine pipelines at sea as per figure 19 in the left side. It also comprises storage facilities which are filled up during the summer months when gas consumption is low in Denmark. In winter when consumption starts to exceed the daily gas production, production is supplemented with gas from the storage facilities. Moreover, gas from the storage facilities is used in situations when the supply from the North Sea is disrupted (Energinet.dk).

Figure 19-Danish gas market Source: Energinet

Nord Pool

A brief introduction of the electricity market in Denmark was found relevant to present in this section. Although, is about heat what we are constantly talking, electricity is generated in CHP plants and therefore there is a great interrelation between both electricity and heat markets. Electricity can be traded both bilaterally between generators/traders and distribution companies/end-consumers/traders and via the Nordic Power Exchange (NordPool). NordPool then is a series of international electricity trading markets, incorporating the Scandinavian and Baltic countries. The reason why it incorporates the adjoining countries is because electricity needs to be consumed as it is produced and therefore, electricity demand will be found in the overall system when there is an excess somewhere.

Hourly power contracts for physical delivery during the next 24-hour period are traded in the spot market (NordPool Spot); owned jointly by the Nordic Transmission System Operators (TSO's).

On the spot market, the market price is settled for every hour and for every regional area. The TSO's also run an intraday market for physical trade called Elbas. At the Elbas market, electricity can be traded up to one hour before physical delivery. Two other markets also exist; the regulating power market and the reserve capacity market (DEA, 2012) (McCormack, 2013).Today the electricity market is well-functioning, fully implemented and operated by the state-owned TSO "Energinet.dk" which has the responsibility for the operation of the market, together with its sister organizations in Norway, Sweden, Finland and the Baltic States.

The Danish retail market - or end users' market - has been liberalized since 2003 which means that it stimulates free competition in electricity production and trade and those Danish electricity consumers have the right to choose from whom they want to buy their electricity (Energinet.dk).

Speculation on the market

One peculiarity from the system is that it allows speculation. Electricity coming from wind mills has very low marginal costs. A marginal cost is defined as the expenses that result from the activity of producing one more unit. In this case, the marginal costs from wind power are nearly cero because once the investment has been made; there is only need to pay for the operation and maintenance costs. In this line, in electricity markets where meeting demand and supply play the most important part, there will be more bids on electricity from wind rather than from other sources (Bøldt, Jørgen, April 2015). That can affect the system negatively, but polices can be drafted to address this issue in the best possible way in order to provide a fair competition. Thereby, it does not hinder potential transitions.

Heat prices

The price of heat is based on its provision cost to the consumer with no local subsidies, baring vulnerable groups. District heating in Denmark is diverse, and split into many small networks throughout the country, all with different organisational structures and reasons for existence, and as a result the price of heat varies depending on the circumstance of the supply.

The more efficient plants, the lower the prices will be. Furthermore, continued technological improvements mean that more electricity and heat can be generated from a given amount of fuel (Bøldt Jørgen, April 2015). 50% of heat in Denmark is supplied by public utilities, including the large producers of energy such as DONG and Vattenfall, and 50% is supplied by private cooperatives, which include farmer operated systems supplying villages (DBDH, 2011). Three transmission companies: Hofor, CTR & Vers (Bøldt Jørgen, April 2015).distribute the heat in the major networks in Denmark (see picture from technology dimension). Each are tasked with the purchase of heat from production units, heat generation to provide their own peak-load and back-up unit requirements, transport through the transmission system and sales and billing of the relevant consumers. Each transmission company is also tasked with expanding the existing network (McCormack, 2013).The way these companies try to calculate the heat demand is on a daily basis by taking into account weather forecasts, previous year's data, experience, wind direction and many other factors in a demand driven way (see "end user" section from technology dimension). After they come up with the heat demand, they send the numbers into the heat market, waiting for bids.

All the issues mentioned above are used to set the tariffs for people connected to the grid of DH. "*Balanced and fair heat tariffs are vital to ensure both customer satisfaction and system sustainability given the particular relationship between the district heating supplier and its consumers*" (IEA; p.108, 2004). Tariff regulation must ensure consumers' protection from unjustifiably high prices (ibid) and in that regard, special tariffs need to be adapted to specific situations. In Nordhavnen, for instance, due to technical modifications on the infrastructure to shift to LTDH technology, residents will be paying the heat bills differently until the new systems replace completely the obsolete one.

<u>Consumer ownership</u>

Almost all district heating companies are owned by the consumers, either directly as consumer co-operatives or indirectly as municipally owned companies. Thus, the consumers elect members for the board of directors directly or indirectly through public elections. This gives certain benefits such as:

a. All company profit is given back to the consumers at the end of the year or is transferred to the next year to lower the heat price. In transitions this point can be crucial. In the case of case, this is really well appreciated as it will be seen in further sections;
b. Management will be encouraged to work for good consumer services at the lowest possible price;
c. All budgets and prices will be transparent for the consumers and consumers will be more motivated to pay the bills;
d. Some municipal companies have either established directly elected consumer advisory boards, thus benefiting from the advantages of both the co-operative and the municipal ownership; or have privatized the company by transforming it into a consumer co-operative (DBDH).

Economy

The production of oil and gas from the North Sea represents substantial value and has a major effect on the Danish economy via tax revenue, via the impact on the balance of trade and balance of payments and via the profits generated by the oil and gas sector. The production of hydrocarbons has made Denmark self-sufficient in energy since 1997 (see figure 18). The oil and gas activities have had a favourable impact on both the balance of trade and the balance of payment's current account (DEA).

<u>Efficient financing</u>

Financing is a problem in many countries, but not in the district heating sector in Denmark. Most companies finance their investments in networks and CHP plants 100% by international credits at the lowest market based interest rate. Banks compete to offer the best conditions as long as they can see that the security is high. Taxes as it has been seen also contribute to this by incentivizing a low energy consumption. Among other characteristics, security is high due to reasons such as a national stable energy policy; consumers are obliged to remain connected and to pay at least the fixed tariffs; consultants provide know-how on feasibility studies and project implementation; and municipalities guarantee for loans, also to the consumer co-operatives (DBDH).

Example of energy trade: Binomial Norway Denmark: Exchange electricity - heat in seasonal periods

Here, an example of electricity-heat trade is presented to contribute to the district heating regime understanding. In that regard, Norway and Denmark have established an "energy contract" that benefits their individual markets and the overall market, namely, the Nord Pool.

Denmark's trading partner for electricity Norway has seasonal storage hydro. Sweden as well, but in a lower scale. Hydro generation forms 98% of all Norwegian power, and 47% of Swedish power (Nordel, 2008). This storage runs on an annual cycle, with the reservoir varying seasonally. So, Denmark exports a large proportion of the variations in its *wind power*, and the variations in its demand. Historically, the lowest-cost way to smooth those variations has been to export them to Norway (and also Sweden), where large-capacity fast-responding storage hydro plant can easily absorb these variations. "Hydropower output can be adjusted very rapidly as the highly variable wind power flows through the <." (Smith 2012 citing Sharman, 2005).

If Denmark only has wind generation, then it must balance its grid by importing or exporting the difference between demand and wind to Norway.

For Norway to balance its section of the grid, its hydro must vary to complement variations in Danish wind. Hence, Denmark exports its wind variations, even when it is only importing power, and not exporting it.

Picture 22-Dovikfoss hydro power plant in Norway

The connections between the hydropower based systems in Norway and Sweden and the Danish power systems provide excellent possibilities for exchanging power generated with low environmental impact.
Thus, the large share of CHP and wind power in the Danish system provides an opportunity to export surplus electricity especially in the winter period when the heat demand is high and hydropower capacity is low - and vice versa in the summer period. (Statensnet).

2003 (especially) and 2006 were dry years. In both years, Norway and Sweden were not as self-sufficient as usual and were forced to import quite large amounts of thermal power from Denmark and Finland. (Smith 2012 citing Sharman & Meyer, 2009).

Key findings

Along this dimension, more concepts has been added to the overall understanding of the DH-technology dimension in the interest of comprehending better the district heating regime. On the district heating market, it is possible to find a complex studding of interlinked markets which makes very difficult not only to set heat prices, but also to supply a constant heat flow according demand.
Consumer ownership is been seen as a very important characteristic through the use of cooperatives for instance to achieve more transparency and engagement. In addition, heat tariffs need to be adapted to each situation and transitions which lead to a change in the general landscape, will force the market to evolve with the LTDH development. And last, but not least, the economy of district heating has shown an efficient management during the last decades compared with other nations. An example of energy trade is finally presented to illustrate how wind and hydro power balance each other from a demand and economic perspective.

Culture

Culture is a relevant dimension because by understanding culture it is possible to understand a society´s values and therefore to explain technological trajectories that contribute society to thrive. According to Oxenvad Christian May, 2015, culture plays a very important role in the Danish society when talking about transitions. However he stated that back in the 1970 and 1980´s was much easier to master plan initiatives with further application. Perhaps it is due to the fact that nowadays democratic processes involved much more people thus leading to difficulties to reach consensus. Nevertheless, in the case of Albertslund, through a democratic process can reach its political ambition of achieving a full implementation of a LTDH network by 2025, despite how slow these processes are and despite the barriers (Appendices VII).

Below, it is presented the events and facts that have endowed Denmark to plan a unique heating system within the Danish energy system:

Cultural background

Danish Society

Danish society has kept a very special relation with the supply of energy and all its developments along history. In fact, Danish energy and climate plans are defining a path towards a low carbon society nowadays (Danish Climate Policy Plan, 2013). In order to start this transition which includes a shift to cleaner energy technologies (Caravalho, 2009), several steps in the DH trajectory from a cultural perspective need to be understood and analyzed in the energy regime to further understand the implementation of a LTDH system.

Picture 23-Wind mills in Kriegers Flak, Denmark's to date largest offshore wind farm in the waters between Møn, Southern Sweden and Northern Germany

Culture dimension

Prevention mind-set

1973/4 was clearly a turning point in the Danish energy case. The fact of making such a quick move places Denmark as a cutting edge country in terms of both decision processes and reaching consensus after a great shock as the oil crisis was (Meyer, 2004). Over the years, numerous actions have been taken on the basis of a broad consensus in the Danish Parliament as a result from the crisis – both in order to reduce the energy consumption and in order to increase the share of renewable energy (Danish energy policy, 2012). Nuclear power debate and more focus on wind power for instance are examples that can therefore illustrate the trajectory Denmark has followed in order to break the path dependency and technology lock-in from exogenous energy resources. In this line, several preventive measures have been adopted resulting in a solid energy system. "*Most industrial countries did not have an official energy policy before the so-called oil crisis in 1973-74*" (Meyer, 2004). Nevertheless, for Denmark was different. In the heating sector, it is possible to mention that a stable energy policy since 1976 in which municipal planning and a tradition for co-operation in the society have been important preconditions for CO_2 emission reductions in Denmark (Ramboll, 2015).

Picture 24-renewable energy mind-set

Energy (heat) as a public good

The district heating companies in Denmark are owned either by the municipalities (particularly in the major cities), or by local consumer co-operatives or foundations (Bøldt Jørgen, April 2015) as observed in the previous dimension. To avoid privatization and therefore profitable-oriented businesses that end up in bad quality of service is of paramount importance. For that reason, Denmark has a detailed ownership structure and the system operators are supposed to be completely independent of commercial interests (Meyer, 2004). In that regard, all company profit is given back to the consumers at the end of the year or is transferred to the next year to lower the heat price. As well, the management is encouraged to work for good consumer services at the lowest possible price.

Having such a consumer-oriented system leads to social acceptation among customers. In this line, transitions can more easily take place when some elements from the regime such as user preferences, acceptation and a historical cultural unity come aligned. All of that is embedded within the regime reinforcing the whole and across the different dimensions. For instance, policies can be oriented in the direction a society wants, or markets can incentivize and protect specific segments of the population.

Transferring ownership was equally important for the Danish energy system from a cultural perspective as a result of the complications from the oil crisis. After the first law (1979), it was then approved for the municipalities to develop their own heat plans according to their needs and expectations. In that sense Government power was decentralized resulting in more ownership at a regional level (see picture 18). This had a great influence on the national energy policy and it laid the foundations for becoming a low carbon society.

One example of ownership transference was observed during the interviews. By & Havn Company, owned by the state, has been transferring gradually the ownership and maintenance of the infrastructure to the City of Copenhagen (Ledgaard Kirsten, February 2015) resulting in 95% by the latter and 5% by the former (BYogHavn.dk).

Picture 25-power relay

Example: Nuclear power case

The nuclear power debate in the Danish context is a very good example to show how a society can organize itself in order to face an alternative energy initiative against society´s values. It was finally banned in the 1980´s, although the official energy policy was aiming at the introduction of nuclear power as soon as possible back in the mid 1970´s (Meyer, 2004). In consequence to that, an alternative energy plan without nuclear power and with a higher contribution of renewable energies was presented in 1976. After some disputes, many Danish universities, in collaboration with NGOs (Non-Governmental Organization) supported this alternative plan and successfully finished the debate of nuclear power in Denmark in 1985. In 1990, the overall goal of Danish energy policy shift to promote sustainable energy development and to reduce greenhouse gas emission in an effort to fight climate change (ibid).

It must be noticed that this is a year before of Chernobyl accident, which proves that the Danish society came to the conclusion of no need of nuclear power in their energy system without the nuclear accident argument. In a way, Chernobyl reinforced the position later. This gives clear evidence of the energy direction Danish society in general and energy planners in particular wanted to give to its energy trajectory. However, there are not only historical and ideological reasons, but also technical reasons to support the abandonment of nuclear power. It basically does not match with fluctuating energies such as wind power because it is not possible to shut down a nuclear power plant when the wind is blowing. Instead, CHP plants can be readjusted to change into steam mode or heat production mode according to wind fluctuations.

Initiative of Nordhavnen

When designing urban settlements, Danish urban planners always take into account culture and place identity. An example is the expansion of Nordhaven in which "*the traces of culture already found in the area must be developed and become active parts of the new city district*" (Nordhaven urban strategy, 2009). This is a heritage that really characterized Danish society and Nordhaven, also called the sustainable city of the future, is also aligned with Danish values when urban planning takes action. Sustainable energy supply will be an important aspect of the vision of Nordhaven (Nordhaven urban strategy, 2009) and the heating sector expected to be implemented there will be cutting edge. In fact, a LTDH will be indeed implemented in order to reach new knowledge about possible barriers (technical, social, etc.) that might present during the testing process.

Key findings

Culture is a relevant dimension because by understanding culture it is possible to understand a society´s values and therefore to explain technological trajectories that contribute society to thrive. In addition to that, every country has a particular culture and a different identity that lead to special decisions thorough their history. Some of these decisions in the Danish case imply a shift from an energy dependent country by importing primary energy resources to a complete independent energy nation towards a low carbon society. Another successful decision was the process of decentralization and the gradual empowerment to municipalities from the state level in order to develop heat plans. Two cases, namely, nuclear power debate and Nordhavn project are also presented in this section to give examples of the Danish approach, so a LTDH implementation can be better understood. All of that is embedded on the cultural mind-set of people in general and of planners more in particular.

Case study: Application of a LTDH system in Nordhavnen

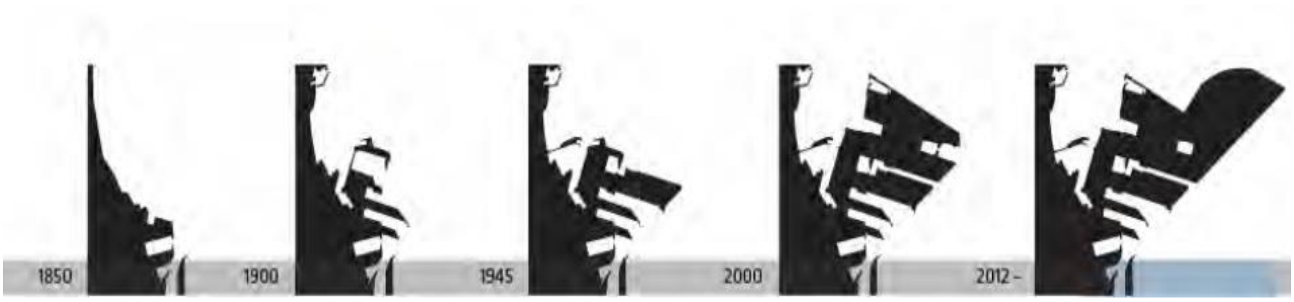
The Nordhaven case is a relevant project for this report because of a very important reason: an energy laboratory is taking place there at this very precise moment, so the theoretical view of technological niches can be better understood and the trajectory of DH can therefore continue. As a result of that, a low-temperature district heating system is being tested right now (since April 2015) in order to analyze barriers, problems and challenges for further implementation and future upscaling process in the rest of Copenhagen once that it is proved to be successful. Success here means a perfect integration of the different components or dimensions that make up the current district heating regime. These dimensions as previously explained and described are technology itself, policies related, market, and cultural setup.

Following this line, history and background and cultural mind-set which help to shape policies trough institutions, lead to the development of the technology in which the market operates. In order to understand the district heating sector in Nordhavnen the author deemed it prudent to provide a brief overview of the sector. The objective is not to go into intricate technical details but rather to illustrate the main components where a low district heating technology is being born and further develop with the purpose of being implemented in the near future.

General overview

History/background

Nordhavn or Nordhavnen (North harbour) is situated at the Øresund coast, in the North-East part of the city. The place bears clear evidence of its origin as an industrial area where harbour activities made Copenhagen trade´s businesses flourish since in the 1880´s. It was built literally on top of old Copenhagen by land reclamation projects over the years using rubble and earth from excavations in Copenhagen. In fact, historical maps can show how the area has grown for the last 150 years (see picture below). Further information about the history of Nordhavnen can be found on the appendices VIII.



Picture 26-Landfilling process evolution-Source: Urban strategy, Ramboll 2009

Goal and vision of the Nordhavn project

Only four kilometres from the city of Copenhagen, Nordhavnen vision is the most extensive and most ambitious urban development project in Scandinavia in the years to come. As Copenhagen ´s population is expected to grow by 45,000 more inhabitants by 2025, new ways to accommodate people must be found to give answer to this great demography challenge. Therefore, Nordhavnen can offer sustainable solutions in the face of climate change challenges when designing a new district from scratch. "*Nordhavnen spearheads efforts to improve climate conditions and show how cities can help reverse climate change without losing out on quality of life, welfare or democracy*" (Nordhaven urban strategy, 2009).

In fact, there are some similar cases. The city of Malmo at the other side of the Øresund coast in Sweden gives a world class example for sustainable living of how an industrial wasteland, as the defunct shipyard was, can be transformed into a spotless eco-district (Malmö Stad). In a similar way (the Copenhagen way), Nordhavnen urban development project entails several components that will contribute to create a sustainable and liveable district. The main focus is being put on: Close contact with the water, Identity and history, Sustainable mobility, Green areas and Sustainable energy.

Picture 27-Nordhavnen 6 themes Source: Urban strategy, 2009

Project actors

Here, the different actors taking part in this urban development initiative are presented. As it can be seen below, most of them are consultancy companies:

Actors	Short description
By & Havn	Partnership to develop areas in Ørestad and Copenhagen Port
Ramboll	Engineering Consultancy
COBE	Architecture and design company
Polyform	Architect studio which works with urban spaces
Sleth MODERNISM	Architecture and urban planning company

Table-6 Nordhavnen actors-Source: BYogHavn.dk; Cobe.dk; sleth.dk

It is important to make here a distinction between the actors that are in charge of the urban development project which entails transport, water supply, sewerage, street lighting, etc. which can be seen in table 6 above, from the energy actors involved in the energylab (see table 7 below). These latter actors such as Hofor or Dong energy work together in order to find out new energy possibilities that will contribute to the overall urban development in Nordhavnen.

Sustainable energy supply

Sustainable energy supply will be an important aspect of the vision for the sustainable city of the future (Nordhaven urban strategy, 2009) which means to provide a reliable, affordable and renewable energy service. This provision must integrate electricity, heating and cooling with the most appropriate energy technologies and energy sources possible. Nevertheless, a completely shift to an entire renewable energy system is not expected in Nordhavnen. Instead, a renewable energy penetration in the system as high as possible is wanted for Nordhavn while the whole of Denmark pursues the objective of becoming fossil fuel free by 2050.

Picture 28-Sustainable energy source COBE, Sleth, Rambøll

Energy resources of Nordhavnen

Several local energy sources are considered to be part of the sustainable energy framework of Nordhaven such as:

- Geothermal heating with heat coming from the ground deep below Nordhavnen
- Solar energy
- Wind energy
- Groundwater used for cooling purposes
- Solar cells in the long term

Together combined with district heating technologies based on biomass and seasonal heat store, and electric batteries (both from EVs and/or large batteries (Ledgaard Kirsten, February 2015), all these sources will shape the energy system of Nordhaven as envisioned in the urban development project. Please see the grid developed of the Nordhavnen future energy system in the appendices I.

Energy lab: creating spaces for innovation

Energy consumption is expected to be very low in Nordhavn compared with that of similar city districts. That is partially because an energy laboratory will take place in the area and further energy experiments and energy innovations will be tested to discover new and more efficient possibilities which will lead to energy savings. EUDP (Energy Technology Development and Demonstration Programme) which is supported by the Danish Government in order to achieve an energy sector fossil-free on time, has decided to provide support for research and demonstration project EnergyLab Nordhavn. Here, a consortium led by DTU (Technical University of Denmark) can show how electricity and heat, energy efficient buildings and electric transport can be integrated in an intelligent and optimized energy system.

The goal of EnergyLab Nordhavn is to develop around 49 projects which include innovative new business models, new energy technologies and intelligent operating solutions, including integrated and flexible energy markets, coordinated operation of the electricity and heating system, energy storage, low energy buildings here and now optimized for energy markets and technologies with flexible switching between sources. The solutions will be used in future sustainable, densely populated low-energy cities around the world. *If we are to exploit Denmark's stronghold in intelligent energy solutions, there is a need for large scale demonstration projects as EnergyLab Nordhavn where solutions can be tested and adjusted in the real world* (says Torkil Bentzen, chairman of EUDP). Nevertheless, it is important to distinguish the energy laboratory as a whole and one particular experiment within the laboratory which is the energy tests for potential implementation of a low-temperature district heating system. In that sense, Energylab works as the pool where new niches can emerge and emerge with potential to establish new regimes.

Energy actors

Nordhavnen is a perfect example of how to integrate different supply types of cooperation between relevant stakeholders from government, utilities, industry and knowledge institutions. The project of Energylab is DTU in collaboration with a consortium that counts with:

Energy Actors	
- City of Copenhagen	- Balslev:
- HOFOR *	- CleanCharge
- DONG Energy	- Metro THERM
- By & Havn *	- Glenn Dimplex
- ABB	

Table 7-Energy actors * Entities that were interviewed in this study

Picture 29-Nordhavnen silos Source: By & Havn

District heating network

In order to reach a non-fossil heat supply as part of the future sustainable energy system by 2035, a state of the art district heating network can potentially play an important role. Nonetheless, to integrate such a district heating in and with both the electricity and transport sectors will be challenging. In that way, smart energy systems can offer a solution, so "smart electricity, thermal and gas grids can be combined and coordinated to identify synergies between them in order to achieve an optimal solution both for each sector as well as for the overall system" (Lund et, 2014). Elaborating on that, smart energy systems need to take advantage of renewable energies and especially in fluctuating renewable energies such as wind power or solar. In this line, district heating can absorb more penetration of renewables due to the dual mode of CHP plants thus contributing to smart energy systems concept.

However, the existing district heating system can be improved. Same researchers mentioned above state that the current DH must be changed radically towards lower temperature district heating networks, identifying buildings (smart energy buildings) as key pieces of these smart energy systems. In order to achieve so, societies must jump into the latest district heating technology, the so called the 4th Generation of District Heating (4GDH) according to many experts in the matter (Werner, Söderholm…). It can offer the many opportunities societies are waiting for in order to achieve fossil fuels–free energy systems.

A brief introduction to thermodynamics

It was found relevant to introduce briefly the second law of thermodynamics because it is related to heat losses in any heat transfer process. As stated by Einstein: "*Energy can neither be created nor destroyed*" (entropy cannot decrease). That means that the overall energy before a transformation process has to be kept equal afterwards. It can only change forms.
Temperature is a form of energy and when two objects with different temperatures are in contact, and then the hottest one transfer heat to the coolest one until a temperature balance is reached in both objects. The heat differences it is understood as heat losses and upgraded DH technologies make a significant step forward by reducing the heat losses in these processes. One example can be when heat is transferred from the transmission line to the distribution network through heat exchangers (see figure 17).

This leads to the temperature change equation which is: $Q = C\ x\ m\ x\ \Delta T$; where:

- Q: Heat
- c: Specific heat
- m: mass of the body
- ΔT: Temperature change

As it can be seen it is very important to keep ΔT unchanged if we want to keep constant Q or the amount of heat (heat demand). As (Hastrup Jeppe, March 2015) pointed out, ΔT has to be respected when shifting from one system to another, namely from the existing DH to the 4GDH. The lower ΔT is, the more compromised the system is. For that reason in the meantime (during this transition), new tariffs will need to be adapted by incentivizing buildings that can comply with a suitable ΔT.
Below, figure 22 of LTDH is presented to better understand this thermodynamics principle.

Low-District Heating Network (LTDH)

If fossil fuel independence is wanted in both electricity and heating sectors as it is the Danish Government ´s goal by 2035; it is imperative to reduce heating demand of low-energy and refurbished buildings and LTDH can operate in such conditions (Brand, 2013). A LTDH will supply both space heating and domestic hot water. These are two core elements that must be defined:

- Space Heating (SH): SH accounts for the amount of space that needs to be heated in order to comply with the comfort temperature established by the Danish Energy Agency which is 20°C to 22°C. (ibid).

  Most of the Danish building stock consists of buildings built around the 1970s ("existing buildings") (ibid). On average they have a heat consumption of 200 kWh/(m^2.a) that accounts to supply for heating, cooling, ventilation and domestic hot water, whereas "new buildings" by Building Regulation 2010 must not exceed of 63.5 kWh/m2 per year for a new 150 m^2 house.

  Therefore, it is possible to see how important it is to focus on the existing buildings in LTDT in order to refurbish them thus leading to better insulation and heat conservation. Some of the measures taken for existing buildings within district heating areas and natural gas areas include the ban to install new oil furnaces from 2016 which are very energy consuming (Our future energy, 2011). In figure 20, it can be observed the tendency towards more energy efficient buildings over time, although the yellow line represents an increase in the buildings stock (existing + new). In a way, the heating system becomes dependent on the building structures which lead to establish these key synergies between smart electricity, thermal and gas grids. One problem at this point is that the new buildings would be less likely to have the same ΔT as existing buildings. For that reason, a new tariff system will be adapted to incentivize lower-temperature returns and penalized higher-temperature returns. It can be seen how the system slowly finds new ways to adapt and survive in the new regime.

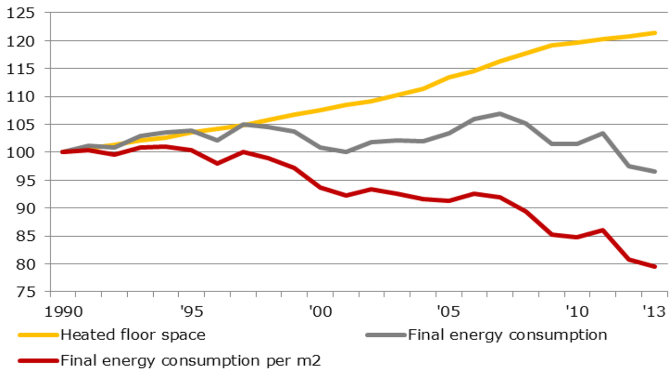


Figure 20-Energy consumption for heating in households Source: DEA

- Domestic Hot Water (DHW): Delivery of hot water is one of the main tasks for DH. The layout of the DHW distribution pipes should be carefully designed so that there is a separate pipe supplying (DEA, 2014). DHW systems can be divided in: the DHW heater (DH house substation) where the DHW is heated from cold potable water; and the in-house DHW distribution system, i.e. pipes connecting the heat source with individual taps (Brand, 2013). See figure 21 and 22 on the right and below.

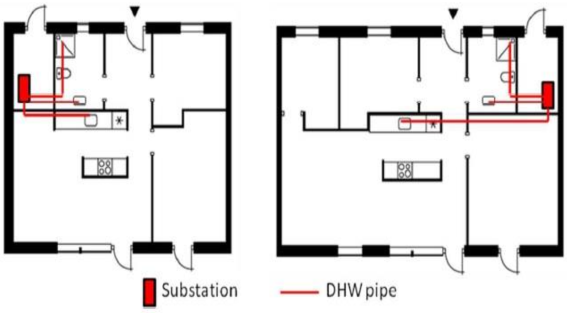


Figure 21-layout of DHW pipes Source: (DEA, 2014)

  - Legionella: DHW should be delivered to every DHW tap with minimal temperature of 50°C in order to comply with the technical configurations of a LTDH system, but the temperature can drop to 45°C during peak situations as per Code of Practice for domestic water supply installations (2009). One problem at this point is the risk of Legionella which proliferates at that range of temperature. Supplying DHW with no increased risk of Legionella requires that the overall DHW tank volume is below 3L (to minimize the total volume of each flat to less than 3 liters, thereby reducing the risk of legionella) (Yang et, 2014). However, data from the interviews highlight that this is a minor concern (Oxenvad Christian, May 2015 & Jørgen, April 2015) (See appendices VII).

At the end, LTDH with a supply temperature of 50°C can be used for the delivery of DHW with the desired temperature and without increased risk of Legionella if the DH substation and DHW system are designed for the low-temperature supply conditions (Brand, 2013).
Below in figure 22, it can be observed the transition of DH would have in the building.

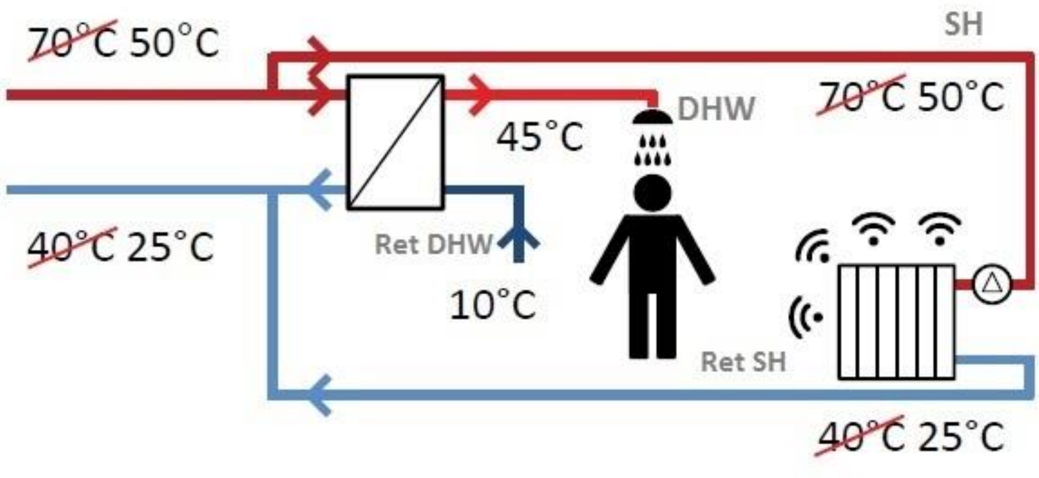


Figure 22-LTDH in the building Source (Brand, 2013).

In figure 22 above it can be seen how the temperature is supplied at 50° C to dwellings instead of at 70° C. From here, it will either go to supply Space Heating (SH) through the radiators to maintain the room around 20 – 22° C, or to supply Domestic Hot Water (DHW) at 45° C. Ret SH (Return SH) is returned at 25° C from the radiators and connects with the Ret DHW joining in a common pipes network in order to be heated again, so the process can start again in a continuous basis. The temperatures differences (ΔT) have to be kept proportional with the current district heating, namely 30° C; Otherwise subsequent technical modifications would be needed as it can be observed in the key findings section below.

LTDH pursues in Nordhavnen to enable low temperature district heating supply aiming at a supply temperature of 50°C at the consumer to meet the end-user's Space Heating (SH) and Domestic Hot Water (DHW) demands in central-northern European climates (DEA, 2014).

It is important here to remind the reader that the current systems in Denmark provide heat at an average of 75°C (supply) and returns it at 43°C according to Brand (2013) as it was seen in the technology dimension section. Therefore (as per figure 22) a remarkable temperature decrease which leads to higher system efficiency can be achieved as it will apply for Nordhavnen.

Why a LTDH?

In dense areas as Nordhavnen is expected to be in 40-50 years, an energy system with a high energy efficiency and high share of renewable energy is possible to achieve. In addition to that, there are several advantages that will be found on the Nordhavnen district heating:

- District heating supply losses can be reduced considerably when reducing network temperatures.

- District heating supply temperature below 60°C makes geothermal plants more advantageous.

- Heat pumps efficiency is higher the lower the required district heating supply temperature is. Then, Low DH supply temperature opens up for a broader range of heat pump technologies (DEA, 2014).

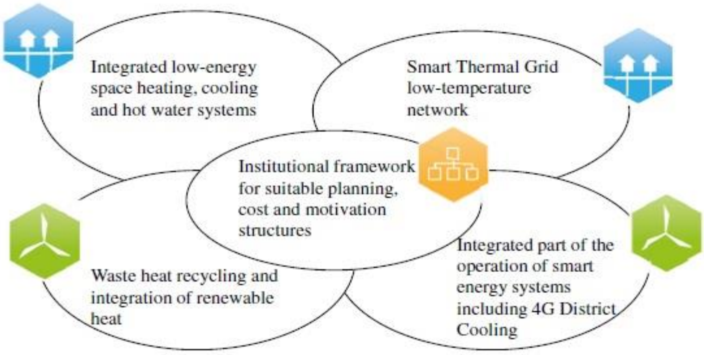


Figure 23-integrations of a LTDH system-Source: (Lund et, 2014)

As it was previously mentioned, buildings are the core focus for LTDH. Therefore, new plans are currently taking place to refurbish existing buildings with the purpose of reaching the same heating demand as the new ones. Therefore, the existing building stock can properly be insulated so heat demand can be reduced at the level of the new mass of buildings. Then it is possible to achieve in both types of buildings a significant reduction of the total energy use for SH of new buildings in order to reach a level equivalent to the energy use for DHW heating (45-50°C) (Lund et, 2014).

In that way, SH & DHW temperatures of both existing and new buildings need to be the same because according to a LTDH system they share the same pipes network. Both services must be aligned at the same temperature because the distribution of them is a "common journey". For instance, if a school is supply with the existing DH and nearby there is a residential house block with a LTDH; to make the corresponding adjustments from the heat exchanger to the end-user can be very difficult to manage. Once that all the houses are finally connected to the heat grid, this problem will not be a problem any longer. However, temporary solutions such as installing a heat pump at the school to get rid of the double overlapped system can work in the meantime (Oxenvad Christian, May 2015).

Objective of LTDH*
Delivery of DHW with the required temperature of 45-50°C DHW at the tap
Design indoor temperature in the buildings, usually 20°C of operative temperature

Table 8-Objective of LTDH source (Brand, 2013)

*New systems has to guarantee same services as the current one

How to implement LTDH?

Although a LTDH system will be designed in an isolated area such as Nordhavnen, it can be further integrated with the current DH. Therefore, heat with different temperatures can be distributed to both new and existing buildings (see appendices VIII).
According to Guidelines for LTDH, 2014, the implementation of a LTDH system can be applied in 4 different manners once the system has been established:

1) Connecting a new development area to an existing district heating system:
   The energy system of Nordhavnen is not going to be an isolated part from the Copenhagen energy system (Ledgaard Kirsten, February 2015). In that sense, Nordhavnen DH will receive heat from the general system. It will not be self-sufficient since what it is wanted to be tested are the technicalities of a LTDH. Then, a question can be posed: - How the Nordhavnen DH system will work in a low temperature if heat is coming from the CPH system at a higher temperature? Next chapter will highlight this main problem by providing an answer to how can these two thermodynamic systems be compatible.

2) Establishing a small-scale district heating system in a new development area:
   This also applies for the Nordhavnen case. The North harbour can be considered a new development area according to the description of the project. EUDP is using that urban space as a laboratory, so potential successful technologies can be further up-scaled. The difference between the first and the second implementation manners is that Nordhavnen is a new development area within Copenhagen.

3) Connecting an existing area e.g. by replacing gas boilers with district heating:
   In this scenario, DH is not being established in the area and a technology replacement unit by unit account for this case.

4) Renovation of an existing district heating system e.g. as part of a general strategy to reduce supply temperature:
   This is the case of an area with district heating and the idea is to jump directly to a full renovation of the entire energy system, instead of moving from a smaller scale as in the first implementation type.

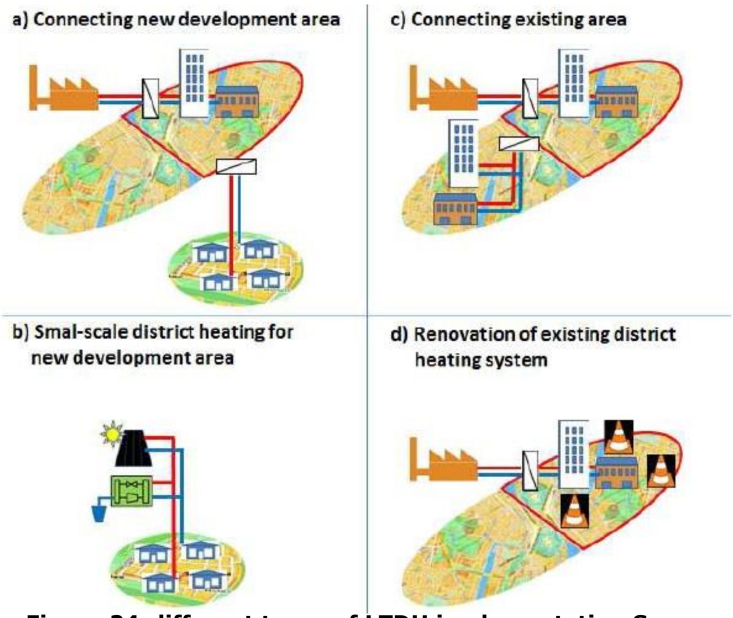


Figure 24-different types of LTDH implementation Source: (Guidelines for LTDH, 2014)

5. Nordhavnen DH´s key findings

Until now, it has been presented the Nordhavnen case in terms of both the project and its future heating system. That have accounted for the data collection from research methods and the interviews as stated in the methodology chapter. However, the next section will introduce the key findings that were found in the Nordhaven district heating research resulting only from the interviews. Therefore, this section is an attempt to identify the main challenges and barriers that a LTDH system, as in Nordhavnen, can face since the energy experiment started in April 2015.

Problems and challenges

Experimenting with a LTDH system leads to some barriers and challenges that must be taken into account at the niche development area before the implementation level. In this line the following problems were identified as a result of the research carried out:

1. Systems incompatibility

It was previously said that Nordhavnen is not intended to have a separated energy system within the Copenhagen system (Ledgaard Kirsten, February 2015). Nevertheless, both systems will be connected due to the fact that Nordhavnen does not own heat generation units. Therefore, it must be supplied from the current DH system. In order to do it, a LTDH system within a higher-temperature DH network (CPH one), can only work by cooling the water from the warmer system to the colder one. *"It is a crime in terms of thermodynamics"* (Bøld J, Hofor April 2015), but the idea behind this initiative of energy testing is whether to find out if it would work or not. The overall objective is to successfully run the system, be aware of the main constraints and understand the limits. Then, in a close future, it might be viable to install such a system in a large scale such as the Copenhagen region.

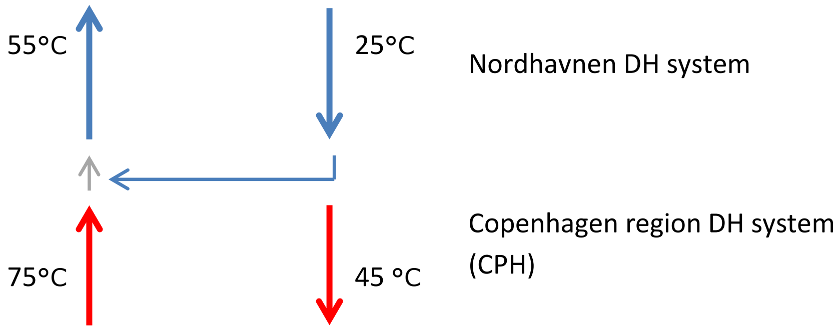


Figure 25-co-existence of both DH systems Source: Inspired form the interview with Bøld J, April 2015.

As it can be observed in figure 25 above, hot water at 75 degrees (from CPH DH) will be mixed with cold water in order to reach a lower temperature of 55 degrees before entering in Nordhavnen. It is intended to lower the temperature from the Copenhagen DH network with the returning water (SH + DHW) from Nordhavnen. In this regard both DH systems can co-exist until all technical configurations are solved in the meantime. For instance, if a school is supplied with the existing DH and nearby there is a residential house block with a LTDH; to make the corresponding adjustments from the heat exchanger to the end-user can be very difficult to manage. Once that all the houses are finally connected to the heat grid, this problem will not be an issue any longer. However, temporary solutions such as installing a heat pump at the school to get rid of the double overlapped system can work in the meantime (Oxenvad Christian, May 2015).

From April 2015, these tests have been running and the DH regime is currently going through several experiments that will develop more and more technical niches, contributing to the history and trajectory of DH in Copenhagen and Denmark.

(Oxenvad Christian, May 2015) from Albertslund can complement this explanation (appendices VII) regarding the LTDH and the existing system: when both pipes are connected, namely return pipes from the former system are linked to the supply pipes of the latter in order to reach the low temperature it needs. However, the heat is not lost because by controlling the pressure of the water flow in the pipes, it is possible to control at the same time the supply temperature without wasting heat by-products from the system.

2. ΔT (Temperature gradient) equals a synergy between policies and markets

Another challenge that comes out from establishing a LTDH within a higher temperature DH is to keep constant ΔT. (Hastrup Jeppe, March 2015) from Rambøll pointed out this issue which can be explained by using the heat equation: $Q = m \times C \times \Delta T$. It can be noticed that if temperature is wanted to decrease (as in a LTDH case) and the heat demand remains the same for the dwellings, then it is needed to either increase the flow (m/pressure) or to increase the size of the radiators from where the heat is supplied (which is more expensive).

As (Hastrup Jeppe, March 2015) pointed out, ΔT has to be respected when shifting from one system to another. The lower ΔT is, the more compromised the system is. Currently ΔT in the Copenhagen DH is 30 degrees, resulting from an input of hot water in the pipes from the source point of approximately 75 degrees and an output or return temperature of 45 degrees. This range of temperature is indeed variable due to the characteristics of each building and/or the weather forecast, and many other factors. For that reason, there is a solution in the system that helps to control and to keep ΔT as close as 30 as possible. This could be a tariff that incentivizes customers to return water as cold as possible and penalizes customers who return the water at higher temperatures.

Tariff difference

As mentioned before, (Bøldt Jørgen, April 2015). from Hofor pointed out that a different heat tariff will be necessary for the residents in Nordhavnen due to the difficulties to keep ΔT constant. Right now in Copenhagen the existing tariff incentivizes customers to return water as cold as possible and penalizes customers who return the water at higher temperatures. However, this tariff will have to be adapted in Nordhavn for the new residents. (Oxenvad Christian, May 2015) from Albertslund also agree that the temperature gradient issue as well will have an impact on the tariff system which will have to be adapted. The fix price in the case of Albertslund for instance will increase while the variable one will be lower due to the future energy savings and therefore economical savings at the end.

If we assume an input/output range of 55/25 will be implemented in Nordhavn infrastructure, then the water returning pipes will have more difficulties to reach a temperature that fulfils 30 degrees ΔT. Instead, a 55/35 degrees range is more likely to be expected where ΔT is 20 degrees. That means as stated before, but now repeated by (Bøldt Jørgen, April 2015) that more flow of water (m) or a bigger surface for the radiators of the house will be required to compensate now the unbalanced heat equation (see a brief introduction to thermodynamics).

(Oxenvad Christian, May 2015) from Albertslund also verified that keeping the temperature gradient is as important as in any thermodynamic process. In this pioneering project in Albertslund there is an awareness of this issue as well.

However, is it possible to go lower? Heat can be supplied through the hot water piping line at 40 and be returned at 10 in order to reach a larger efficiency. However, again it would be very difficult to keep a constant ΔT and more efforts would have to be put in the technology which would not be economically feasible. For this reason, residents in Nordhavn would have a different tariff system.

Picture 30–DH pipes Source: www.generationparknorwich.com

In terms of energy transitions, in this case policy and the market will have to work together in a common framework in order to solve these technicalities first towards the implementation of LTDH and later towards fossil fuel free energy systems.

Other findings

Heat Pumps (HP)

Other findings from the interviews can show how the development of the future energy system will be. In connection to that, HPs are found as key players that will contribute to shape the future regime.

Picture 31-Heat pump

A Heat Pump is a very efficient electricity technology with a Coefficient of Performance (COP) of 3.5 which means that every electricity unit is converted into 3.5 units (Blarke et, 2003). This means that HPs are essential for the future energy systems and especially for the heating sector because they can help to convert electricity into heating, or in other words, electrifying the heating sector thus contributing to a transition towards more electricity in the energy system. This would allow more wind energy penetration to support the heating system thus contributing to synergies across energy subsystems. HPs are not mentioned in the Nordhavnen urban strategy as a key element of the future LTDH although (Ledgaard Kirsten, February 2015) stated that "perhaps" in the future.

Subsidies from 1981allowed HPs to achieve market share in Denmark quickly (together with the incentive from the energy taxes on fossil fuels). After that, the share of renewable energy for space heating grew from 5% in 1980 to 13% in 2001 (Energy policy in Denmark, 2012). Today, market-promotion of initiatives (e.g. package solutions and ESCO models) for energy-efficient heat pumps and solar heating, are being considered to replacing oil-fired boilers with renewable energy solutions (Our future energy, 2011). The problem is that generally it is more expensive than the technology it replaces.
(Hastrup Jeppe, March 2015) from Rambøll pointed out that HPs only operate on an individual scale because "*Large HPs are not able to take high temperatures in the current DH system of 75/45 degrees*

DH network". Therefore, by establishing a 55/25 degrees DH network (LTDH), it opens up opportunities for large heat pumps and thus the possibility of achieving higher rates of efficiency. Apart of HPs, there are other technologies such as floor heating, geothermal energy and electric boilers which can also operate in a very low range of temperature that would benefit from a low-temperature DH system (Bøldt Jørgen, April 2015).

Jørgen Bøld from Hofor points out that regardless the advantages of this energy-efficient alternative to furnaces and air-conditions, the technological implementation faces important economic challenges. First of all, the prize to install heat pumps varies very much with the size. In that regard, small heat pumps are more likely to be installed. However, it is with the large ones that great efficient performance in the overall system can be achieved (also stated by Hastrup Jeppe, March 2015). In addition to that, the "refrigerator liquid" that makes HPs to work is not allowed due to the environmental regulation in Denmark. There are alternative liquids, but once again, it is not economically viable and today biomass boilers are much cheaper.

In Denmark, the use of heat pumps will increase in the coming years. In district heating, which covers 50% of the Danish heat demand, heat pumps are increasingly used. This enables higher levels of wind energy to be used for thermal purposes, which contributes to the goal of 100% district heating to derive from renewable sources by 2035 and to contribute to an electricity transition. The energy policy report from 2013 states that "For Danes living in areas without district heating, heat pumps combined with solar energy are a good alternative, and with the reduction in the tax on electricity-based heating in the Finance Act, heating based on heat pumps has become a less expensive alternative for consumers". By 2016, these homeowners are no longer permitted to install oil boilers. They can choose between a heat pump, a gas boiler, connecting to a district heating network or another non-fossil alternative (IEA, Heat Pumps for smart grids Denmark, 2014).

HPs also face another barrier which is bad reputation. Due to several experiments (in other energy laboratories) that took place in the past years in Denmark lead to discontent from dwellers. For that reason, promotions and campaigns to incentivize the use of HPs are needed to re-launch them and place them at the core of individual heating.

Social acceptation

Due to time constraints, to interview future residents of the Nordhavnen district was not possible. Nevertheless, the late meeting with Albertslund Forsyning highlighted some of the people´s concern about the implementation of a LTDH. In that sense and since the Albertslund project is an on-going initiative with current social results, it was found relevant to share them here because mostly can be extrapolated to the Nordhavnen case.

Some houses in Albertslund have been physically and technically adapted into a LTDH infrastructure. However not everybody is aware of the long-run benefits of such a system due to the economic investments. It has to be said, that there are some measures that can help in this process. For instance, during several years heat has had a lightly higher price that the real heat cost. Therefore, there are some savings that can be used now to promote the LTDH system by subsidizing the building refurbishment; or loaning the remaining money for the residents that cannot pay the full investment. In addition, there are private houses that to invest in radiators or insulation is a more difficult task of convincing than compared with house aggrupation's. Social campaigns in this regard are slow processes and often dwellers do not see the full picture including the benefits for the long-term. Besides, Albertslund houses 101 different nationalities which make the communications tougher.

6. Discussion

Gradual improvements within transitions

The focus of the report is to highlight the benefits of a Low-Temperature District Heating (LTDH) network in Copenhagen as a result of studying the dimensions of the district heating trajectory in Denmark. In order to do it, the on-going project of Nordhavnen shows the main challenges and barriers to implement such a system in a higher scale as it was said, in Copenhagen. But before transforming the current system into a LTDH system, a transition process must take place in which both systems will try to co-exist.

Geels (2002) recognizes that radical transformations are difficult to happen, since all the elements on a technical regime are aligned and connected to each other. When all these elements, components or also defined in this body of work as dimensions come aligned, then a window of opportunity might open new possibilities. This breach on the landscape can be used by specific technologies to upscale the MLP levels and evolve from the niche status to find its place in the regime and step by step consolidate into a new position in the overall landscape.

However, it is lightly different from the purpose of the LTDH technology in this context which is gradually improving the DH framework. The MLP theory in that sense is being challenged and a supplementary scope can be found in this study. An incremental improvement within a transition process is therefore more realistic in practice rather than a total break with reality. However, Geels (p.3, 2002) also recognizes the importance of incremental improvements which includes in his definition of the MLP concept: "*technological regimes can create stability because they guide the innovative activity towards incremental improvements along trajectories".* This can lead to transitions and thus modify rather than change both the district heating regime and landscape, at least in the short term. Elaborating on that, modifications on the current regime take place in a slow but progressive pace, leading to real transitions. A transformation of the system then is possible to achieve and Danish energy ultimate goals, which are to phase out fossil fuels by 2050, can play an important role. Therefore, 2050 is the point when the district heating trajectory comes to an end in this report as it has been analysed until that year, while 2020, 2035 represent essential milestones in the process. Nevertheless, 2050 can potentially mark a turning point for a wider transition in a bigger picture which can be analysed in future studies.
In the next figure 26 below, it can be observed the path followed during this report:

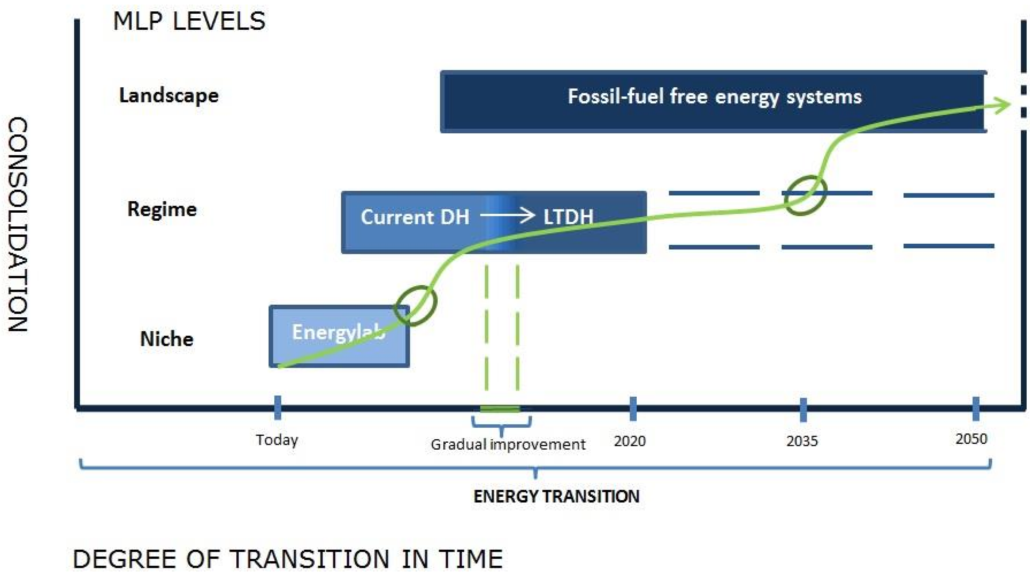
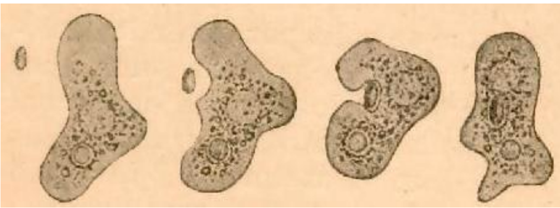


Figure 26-A gradual improvement within general energy transitions

Several secondary transitions take place to support the overall energy transition and thereby the technological gradual improvement can be seen as an internal transition process to reach the landscape level, namely an energy system independent from fossil fuels. Although, it is at the regime level where technologies achieve a high degree of consolidation, reaching the landscape level results in a final stabilization. It is important here to understand the landscape level as the wider context in which the regime operates. Therefore, that applies to take into account 2035 and 2050 energy goals to reach the Danish future energy landscape, which are: To unlock both electricity and heating sector, and the whole Danish energy sector, respectively, from fossil fuels. Nevertheless, by focusing on the regime (the level where certain trajectories can take form), it is possible to see the effect of today´s policies and how they affect to the trajectory that will lead to this particular 2050 scenario.

Now, Danish society is aware of the general landscape (MLP level) to be achieved and in order to reach that scenario, it is needed, not only new policies, but also to take special steps such as introducing new technologies to break the current lock-in. In fact, failure to do it will result in a different trajectory of what is expected and planned nowadays. That is why is very important to continue with more energy experiments at the Energylab where new technological ideas are germinated, flourished and further matured towards consolidation. Although Energylab can play an important role for further energy developments, the degree of transition of this laboratory concerning the LTDH finishes at the point where the regime starts evolving and takes the relay departing from a consolidated technology (see figure 26 above). This is because it has already fulfilled its mission to provide a solid technology and has contributed in a particular point in time to the energy transition. In figure 26 above, this can be noticed where the green curve (DH trajectory) goes from the energy lab to the regime level and thereby all the contribution from the niche level for the overall energy transition, as analysed in this report, ends there.



Picture 32-Ameboid absorption process-Source: www.naturalezadearagon.com.

However, co-existence between the existing DH and the 4GDH must be seen because LTDH will not be about a radical implementation. In line with this, heat exchangers will need to be adjusted to support both distribution networks: a 75°C/45°C with a 55°C/25°C for supply/return networks (figure 24). Temporary solutions such as installing heat pumps at specific spots can be done to get rid of the double overlapped system in the meantime. Both systems then need to work together, individually regarding distribution of heat, but integrated regarding transmission. And finally the old system will be replaced after a slow process of adaptation, aiming at becoming a fully operational upgraded system. As in picture 30 on the left side, the big amoeba, representing the relentless LTDH absorbs the small one, representing the existing DH. At the end, they will co-exist until the big amoeba imposes itself.

However, the new technology, namely a LTDH system, has some technical peculiarities which represent a mis-match with the established technology. It has been seen the incompatibility among the two systems due to an infrastructural barrier. In that regard, the existing DH system will be cooled (decrease pressure) to satisfy the temperature requirements to run a LTDH system and for that reason the energylab will be on charge of developing the LTDH until co-existence of both systems can be achieved. In addition, the ΔT in both systems needs to be respected and that requires more water flow (more pressurized) or to increase radiators' size of the house to compensate heat balance ($\Delta T = 30°C$). At the same time, these incompatibilities lead to provide a different tariff for the residents living in that area resulting in a market exception.

By making both systems to exist at the same time, then evolution in technological systems can take place. As it has been mentioned in the theories chapter, evolution is a process of unfolding and reconfiguration (Geels, 2002) and can lead to technological transitions in which these new configurations can result in new paths and trajectories.

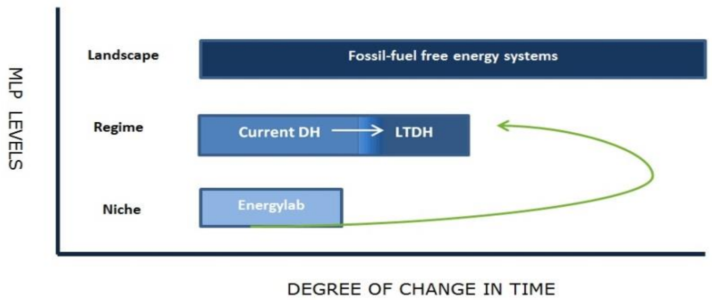
After first turning point in figure 26, it can be seen a perfect example of an internal transition step, also defined in this report, as a gradual improvement of the DH technology. As with the previous MLP level, namely the niche level, the regime also continues in time, but here it is only presented the contribution to the energy transition and that is the reason why it does not go beyond 2020. After that, from the regime level, an asymptotic behaviour can be observed in the green curve until the second turning point is reached. That is at 2035 where the LTDH cease to rely on fossil fuels and shifts to biomass fuels for instance, which are to some extent renewables. After this point, the DH trajectory will follow towards freeing the energy system (including transport) from fossil fuels. It can also be noticed that the trajectory continues since trajectories never stop evolving. However as previously stated, the aim of this study is to analyse DH trajectories within a defined landscape and a time horizon, namely 2050 horizon.

In conclusion, the understanding gained from studying the dimensions that make up the district heating regime in Denmark supports the idea of matching the multi-level perspective with the Danish district heating trajectory. The only one thing that differs is that MLP applies for the transition itself and not for the elements that make internally the transition work. Following this, a LTDH system entails an internal continuous improvement. For that reason, a first transition takes place which is moving from the 3rd to the 4th DH generation, in order to contribute to achieve the overall transition towards a fossil fuel free energy system where 2020, 2035 and 2050 are known as defined energy milestones.

There are two aspects from the figure 26 above that must be taken into consideration:

- The scale of the horizontal axis called "degree of transition on time" is not proportional. In that sense, the time period between today and 2020 is not comparable with the time period between 2020 and 2035 or 2035 and 2050. The former period can be taken as a zoom in whereas the latters are more in the same time line proportion;

- The other aspect to consider in figure 26 is that the boxes from both the regime and niche levels do not continue along time. This is due to degree of change and reconfigurations that each level houses in this theory application to the real world. In other words, the green curve from the figure depicts the extent of change from the niche level, crossing the regime and finishing at the upper level, namely the landscape. For that reason, the green curve, DH trajectory, represents a continuous development to make possible the transition towards changing and/or modifying the overall landscape of phasing out fossil fuels.



One more consideration to take into account is that the current experiments taking place at Nordhavnen (energylab) would be directly implemented at the regime level. In that sense, a window of opportunity is facilitated by the Government in order to achieve the energy milestones (2020, 2035 & 2050).

Figure 27-technological leap

For that reason, it is convenient to take a look to the types of transitions defined by Smith et (2005) due to the fact that somehow a window of opportunity is skipped in this transition and a technological leap takes place to an updated version of district heating. By improving the system in such a way there are elements from three types of transitions that apply to this case: *Purposive transitions*, *Endogenous* *renewal* and *re-orientation of trajectories* (see table 2). It can be observed elements from both sorts of transitions. On the one hand, there is a purpose for the Nordhavnen project, including the energy laboratory there, which is to create strong collaborations between the Danish Government, research institutions and energy companies in order to find sustainable and cost-effective solutions. In that way, the transition thorough 2020, 2035 and 2050 objectives will lead to another system which is the main objective.

On the other hand, a LTDH system also has characteristics from endogenous renewal transitions where changes in the regime tend to be incremental (Smith et al 2005, citing Hodson) as a response to the urban pressures influencing on the regime. In addition, it can be noticed that the DH trajectory is being re-oriented and therefore efficient forces are contributing to shape the future energy landscape after a slow adaptation process. In conclusion, LTDH implementation presents characteristics of these three types of transitions, excluding the emergent transformations as the urban pressures have a solid coordination and a defined direction. The latter transition type was considered at the theories chapter, but as it has been seen in this evolutionary trajectory for the district heating system in Denmark, there is a solid purpose coming from the Government level.

It can be said that current configuration of the system is under pressure and needs urban responses (Hodson, 2010). This pressure is the certain forces that push the regime in a particular direction and thus helps to escape from any path dependency and lock-in in the current system. In this conceptualization, a technological transition consists therefore of a change from one configuration to another, involving substitution of technology, as well as changes in other elements (Ibid).

The report supports that a cutting edge technology by itself has a little role in technological transitions. Only when a new technology becomes aligned with more elements in society such as markets, policies and culture, then it has the potential to move one step forward and become a dominant technology. These elements, also called dimensions in this body of work, can "fulfil functions" (Geels, 2002) and reconfigure the current regime. In Nordhavnen, market through a special tariff system will be aligned with a LTDH technology. In a similar manner, policies have been drafted to promote specific technologies that will perfectly complement the new system such as heat pumps and geothermal energy. As well, policies have contributed to expand the current district heating network leading to higher rate of connection that a LTDH will also use. On the contrary, there are other policies which have banned technologies that do not contribute with the LTDH development, such as electric heating.

Therefore, all the decisions made in the past have led to a final break with the path dependency and thus un-locking the system which now is open for new possibilities as LTDH. The DH trajectory then follows an evolutionary path which will lead into a new energy system, modifying the urban ecosystem.
To better understand the DH trajectory, below, it is presented the District Heating trajectory of the Danish case along its history:

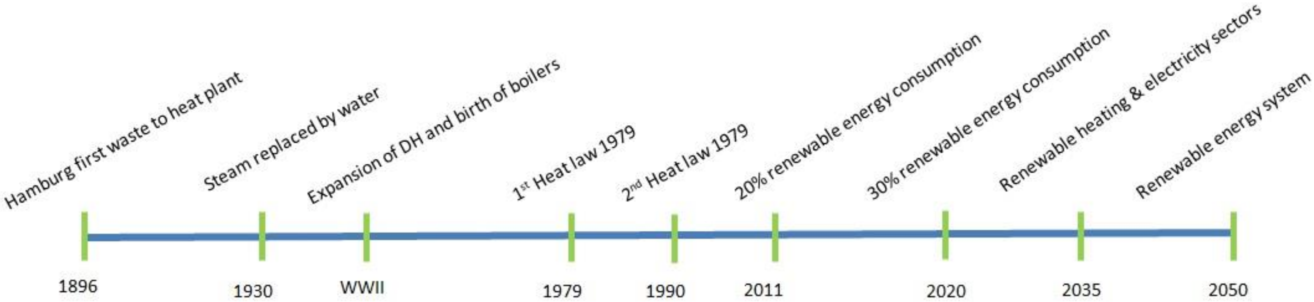


Figure 28-Danish District Heating trajectory and future energy milestones

As it can be observed in figure 28, the Danish history can be told from the Hamburg thermal plant that was used as an example to build the first waste to heat plant in Frederiksberg, Denmark a few years later. That was the 1^{st} generation of district heating technologies and as soon as steam was replaced by water as the heat carrier, great efficiency was achieved in the system giving rise to the 2^{nd} generation of the technology. Later, WWII resulted in the perfect excuse to expand the network due to the entire back-up infrastructure built because of the black-outs. After this point district heating development continued until the 1970´s where lower temperatures were taking place thus giving rise to the 3^{rd} generation of district heating.

It can be noticed that the oil crisis of 1973 is not included on the time line. It was decided to dismiss it because there was little influence for the district heating trajectory. While the oil crisis allowed a reorientation of the energy policies towards more renewables penetration in the energy system plus achieving an energy independence status, there is low impact on district heating. Undoubtedly, district heating was improved and the connection rate was increased, but 1973 was not a decisive point in time to consider in the trajectory of district heating. However, it can be argued that the oil crisis triggered a number of initiatives and policies such as the heat plan of 1979 in which municipalities were urged to develop heat maps. That was a great step in the Danish energy system in general and in district heating sector in particular. Therefore, the benefits for District Heating from the oil crisis can be considered as an indirect consequence rather than a direct one. Later, the second heat law came in 1990 converting the heat only plants to combined heat and power plants. Reaching the present, it is possible to find the milestones that will leverage the energy transition towards a fossil fuel free system: 30% of the energy sector is expected to be renewable by 2020; the entire electricity and heating sectors by 2035 and the whole energy system by 2050 will have definitely phase out fossil fuels.

The Danish district heating trajectory has followed an exemplary pace in regards with other nations. In that sense, it is unique and not replicable. The success can be explained from the interaction and integration of the different dimensions, making up the DH regime. Danish history and cultural background have helped to shape heat policies trough institutions, leading to the development of the technology in which the market operates. This helps to understand the current situation of District Heating and where we are now, but it will inexorably lead to configure the energy system of the future.

Is a LTDH the right path?

As it has been said, several studies support the concept of a LTDH system as the heating system of tomorrow. Implementing a LTDH can offer many fruitful synergies across the energy systems that will help to achieve all the above mentioned goals towards a sustainable energy system. In that way, smart energy systems can offer a solution, so "smart electricity, thermal and gas grids can be combined and coordinated to identify synergies between them in order to achieve an optimal solution both for each sector as well as for the overall system" (Lund et, 2014).

The transition from fossil fuels and nuclear-based energy systems in general to sustainable energy systems requires flexibility in demand, more intermittent renewable energies such as wind and solar, and to refurbish the existing stock of buildings for better heat insulation and energy conservation (ibid).

Same source also states that "Heat Roadmap Europe" concludes that this technology is the key for the future energy systems and also emphasizes the need of restructuring the current DH system into a more interactive way with low-energy buildings. Only in that way, challenges and barriers will be addressed. In that regard, SH & DHW temperatures of both existing and new buildings need to be the same because according to a LTDH system they share the same pipes network. Further studies can look at potential opportunities that can be taken advantage of, in order to overcome such challenges. Nonetheless, lesson learnt from the Energylab show that if a reconfiguration process has to take place as part of the so-defined transition; potential technologies can enter to play due to economic feasibility and/or technical viability in this new scenario.

Therefore, new possibilities are open up if a LTDH system is installed such as:

<u>Heat Pumps</u>

Heat Pumps (HP) can add flexibility to the energy system due to its storage characteristics. Furthermore, by replacing oil and natural gas boilers in individual houses by heat pumps and biomass boilers (Lund, 2009), so much can be gained.

Wind power in Denmark during 2014 accounted for 39% of the overall electricity production, but most of it could not be used because the system was not prepared for the surplus of wind. The main problem was to integrate this extra electricity into the system (Ledgaard Kirsten, February 2015). Currently, Denmark is investing in wind power and by 2020, 50% of national electricity consumption will come from wind power (Energy policy report, 2013). That leads to figure out a solution regarding the excess of wind. Excess of wind can feed heat pumps and a renewable tariff based on ''excess'' wind would be sufficient to operate heat pumps (Hewitt, 2012). HPs can balance the grid, providing stability to the overall system and they can be combined with electric boilers when it is required. Hot water storage as well cannot be underplayed in the efforts to integrate greater amounts of electricity onto the network (Ibid).

Another important aspect from HPs is that they achieve higher coefficients of performance when a LTDH is taking place and as (Hastrup Jeppe, March 2015) stated the current DH system cannot perform at the same high efficiency rate as if it was with a LTDH. Today HPs only operate at individual scale, but if the LTDH is implemented there would be great opportunities for large HPs to operate combine with CHP plants.

In conclusion, an optimal solution seem to be individual heat pumps in those areas where DH infrastructure is not economically feasible and a low-temperature district heating network in the denser areas (Lund, 2009).

Geothermal potential for DH

The Danish city of Frederikshavn, in Northern Jutland, Denmark pursues the goal of becoming 100 % renewable energy city and geothermal power can contribute to a large extent. In fact, a LTDH can use low geothermal temperature to make operate heat pumps efficiently. All combined with wind power, waste and solar heat (Østergaard et, 2011). Denmark in general is in a geological stable region, but Frederikshavn is located in an active geological area that can be used to produce district heating through heat pumps (58 °C at 2000m).

Picture 33-Geothermal energy source: www.freefusion.org

This temperature level is very low and it can be used as the heat source for an absorption heat pump that will be mixed with hot steam from a CHP plant. In that way, electrical and thermal outputs of the waste incineration plant are reduced, but the added heat from the HP compensates by far (Ibid).

Therefore, LTDH have the possibility to recycle heat from low-temperature sources and integrate renewable heat sources such as geothermal heat.

On the other hand, the implementation of a LTDH system can also involve negative consequences with current technologies because there is not logic on keeping them during the transition towards fossil fuels free systems. In order to illustrate this, the dismissal of electric heating will be presented below:

Dismissal of Electric Heating (EH)

Nowadays, there is no electric heating in Denmark. It was banned in the 1970´s. Electric heating was abandoned because there was no room for it in the energy system of that time. But, what were the reasons to dismiss such technology?

With the first law on heat supply and the empowerment of local authorities, it was stated to oblige new and existing buildings to connect to public supply to connect to individual natural gas or DH systems. It still remains in effect for new buildings. However, the ban on installing electric heat in "new buildings" dates back to 1988 in order to achieve more efficient energy utilisation whereas the ban was extended to electric heat installations in existing buildings with water-based central heating systems in 1994. Thereby, the installation of domestic electric heat in areas with public supply or zoned for such supply was prevented (DEA).

At the end, both the obligatory connection and the ban of EH contributed to ensure that a certain number of connected consumers were maintained in order to make the energy supply companies profitable. As it has been seen, district heating systems need dense areas and a high connection rate; otherwise, the investments in infrastructure (pipes) cannot be recovered. It was also explained in previous chapters that the areas where it is not feasible to install the DH network, heat would there be supplied by individual heating with technologies such as natural gas or heat pumps.

Heat pumps and geothermal energy have been presented with the purpose of supporting a LTDH system. Following this, a LTDH can give birth to new technological possibilities which can contribute to improve the overall system efficiency during the so called energy transition. In addition, it was presented the dismissal of an obsolete technology in the Danish case, namely, electric heating, in order to illustrate the evolutionary trajectory of district heating by showing the replacement of an energy niche.

Electricity transition

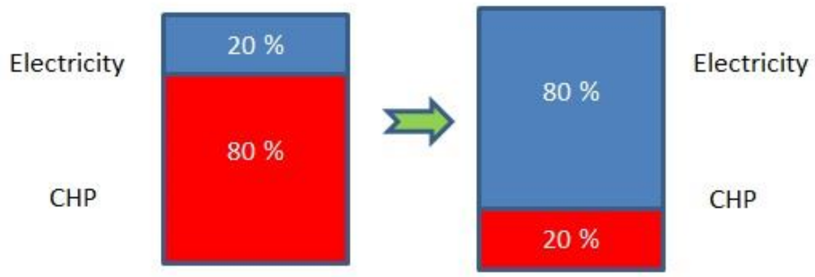


Figure 29–electricity transition Source: Inspired by meeting with Hofor, Bold, April 2015

It is been mentioned over and over the energy goals that Denmark is aiming at. Therefore and in this process of energy transition, it has to be added that the Danish energy system will first shift gradually to an electricity–based system by increasing the amount of wind mills, before freeing completely the energy system. In this line, more penetration of wind power will lead to the use of storage technologies such as heat pumps and hot water storage in order to make this scenario possible. As it was explained, the system will gain flexible energy demand and energy will be conserved as much as possible everywhere across the system.

If there is more electricity than what the system can handle, then electric boilers for instance would start working. However, solutions in this matter should be on the promotion of electricity storage technologies (ibid). Compressed Air Energy Storage (CAES) technologies which are based on electricity could also work in this future landscape, as well as hydrogen storage (Bøld J, Hofor April 2015). Nonetheless, these technologies are not foreseen in the future Danish energy system so far. On the contrary, electricity as observed in figure 29 will be the key gate for smart grids and synergies across the energy sectors, including transport by the use of electric vehicles for instance (Lund et, 2008).

LTDH will adapt its heat generation units such as CHP plants in order to integrate all these wind power excess. In that sense, heat production mode will be prioritized compare to steam mode (electricity production mode) in order to allow the system to use uninterruptedly the electricity coming from wind power. As figure 29 above, it can be appreciated that there is a "moving process" from CHP based system into an electricity based energy system due to the expected wind energy penetration in the coming years (Bøld J, Hofor April 2015). Apart from that, CHP plants will reduce their energy contributions to the system thus resulting in heat generation mainly, which would be based on bio-fuels.

Future CHP plants in a LTDH network will operate in perfect harmony with existing and new buildings. They will be fed primarily with biomass, so fossil-fuels will be totally replaced. Thereby, negative agricultural impacts resulting from bio-fuels production will be minimized while at the same time an assemblage of different renewable sources will come to play in order to give shape to the future sustainable energy system in Denmark. In addition to that, sustainable energy systems will interact with the rest of the infrastructure systems in the city such as water supply, sewerage, transport, etc., aiming at becoming an efficient urban ecosystem by closing all the loops and by taking advantage from all the "by-products" from one system to another.

7. CONCLUSION

Currently, Denmark is aiming at phasing out fossil fuels from both heating and electricity sectors by 2035 and to become fossil fuel independent in all the energy system including transport by 2050. With these targets, it is of paramount importance to find technologies that can contribute in this green transition. In that regard, a low-temperature district heating technology (LTDH) can offer a good chance due to its efficient operation. Implementing a LTDH system also entails great opportunities for other technologies that can take advantage of this low temperature characteristic. Therefore, heat pumps and geothermal energy can potentially play a key role in the future energy systems as a result of lowering down the heat carrier temperatures in the distribution of district heating, all contributing to more efficient, less polluting and more renewable systems.

Thus, considering all the above, in the present study, it is been discussed what are the challenges and main barriers to implement a lower temperature district heating system in the area of Nordhavn with a further potential implementation in Copenhagen, Denmark. Currently, Nordhavnen is hosting an energy laboratory which is trying to find out these specific barriers and this study provides an answer to that by an extensive analysis through both research methods such as consultancies material, books and articles, and interviews from the main energy actors involved. In line with this, the Danish Government is supporting this initiative in order to achieve an energy sector fossil-free on time where technologies such as LTDH can be born, mature and flourish before implementation in a larger scale such as the rest of Copenhagen.

In addition, a description of the Danish district heating regime has been presented through its deconstruction into several dimensions such as the technology, policies and markets related and cultural mind-set according to the multi-level perspective theory. Danish history and cultural background can indeed help to shape the right policies trough institutions, leading to the development of the technology in which the market operates. In fact, it was observed that dimensions interplay crossing each other, complementing and supporting the overall district heating regime.

In addition, an evolutionary explanation of the district heating regime has been introduced in the context of an energy transition towards phasing out fossil fuels from the Danish energy system to understand better the challenges and barriers resulting from the implementation of a LTDH. Following this, the Danish district heating trajectory has been presented in this body of work in order to identify such challenges.

The key points from the results and discussion are:

It was found from the interviews that the implementation of LTDH system can lead to several complications if it has to co-exist with an existing district heating. In that regard, a slow adaptation process would take place to make integration of both systems possible. Elaborating on that, the DH distribution network would have to support both the existing and the new DH systems, which represent a challenge. Furthermore, the existing system will have to cool down the heat carrier temperature (or decrease pressure in the flow) in order to be both carried in the same pipe network. Therefore, heat exchangers will need to be adjusted to support both distribution networks: a 75°C/45°C with a 55°C/25°C for supply/return networks. Temporary solutions such as installing heat pumps at specific spots can be adopted to get rid of the double overlapped system in the meantime.

Another challenge from implementing a LTDH system is to maintain the same heat difference or ΔT from the existing system in the new system. If heat demand remains the same and supply/return temperatures are lowered, then the rate needs to be lowered proportionally. Otherwise, technical modifications will be required in order to satisfy the heat demand. In that sense, a new tariff system can contribute to harmonize this problem by incentivizing customers to return water as cold as possible and penalizing customers who return the water at higher temperatures, given an assumed heat supply.

LTDH has been seen as the right path for an energy transition in Denmark towards a fossil fuel energy system and it will play a key role in the coming years. Examples as in Nordhavnen or Albertslund (where a small scale LTDH implementation is also taking place) can offer best lessons to understand the main barriers and challenges concerning this technology.

In conclusion, energy laboratories can be used in urban ecosystems as means to work strategically with transitions due to the fact that it is possible to gain important lessons that can be taken into account at the implementation phase. Furthermore, the study of trajectories as part of transitions leads to the conclusion that several dimensions of the regime need to be aligned thus contributing to improve a technology. In Nordhavnen, market through a special tariff system will be aligned with a LTDH technology. In a similar manner, policies have been drafted to promote specific technologies that will perfectly complement the new system such as heat pumps and geothermal energy; or have banned technologies that do not contribute with the LTDH development, such as electric heating. As well, policies have facilitated an expansion of the current district heating network leading to higher rate of connection, which are important preconditions for a LTDH.

A LTDH can be a step forward for the Danish energy system, leading to reduce heat losses thus saving energy fuels and therefore decreasing levels of CO_2, providing both comfort temperature and a good distribution of hot water service. In addition, it can become part of smart energy grids in which sustainable and efficient synergies will be established in order to achieve resilient and integrated urban ecosystems.

To conclude, it has to be said that Denmark has an active political will that can be seen throughout the analysis of policies towards the achievement of phasing out fossil fuels in the Danish energy system. A strong commitment that includes local initiatives, a public and transparent system, and a special cultural mind-set has proven to be effective in order to take decisions that explain why Denmark can reach these energy targets. A LTDH can then represent an optimal solution to fight climate change, contributing Danish society to thrive.

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