Master Thesis on a

LIFE CYCLE ASSESSMENT OF THE UTILISATION OF EXCESS HEAT IN DISTRICT HEATING SYSTEMS

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Abstract:

The utilisation of excess heat in district heating systems has been proposed as a strategy to reduce the energy sector's environmental impact. In Denmark, excess heat could potentially meet 35-77% of the total heat demand, yet the specific environmental impacts of excess heat usage remain underexplored. This study aims to fill this gap by investigating how the utilisation of excess heat influences the environmental impact of the district heating system in Aalborg municipality. A comprehensive literature review reveals a predominant focus on CO^2 and greenhouse gas emissions, highlighting the need for broader environmental assessments and a clear definition of excess heat. This study employs a consequential life cycle assessment (LCA) to address these gaps with results contextualised through lock-in theory. An hourly LCA model is developed, incorporating hourly heat supply and demand data alongside environmental impact factors for each heat supplier. This approach reveals temporal variations in environmental impacts, emphasising the dynamic nature of the district heating system. Key findings indicate that the environmental impact of excess heat is significant and context-dependent. Allocating environmental impacts to excess heat based on its share of total energy production shows that excess heat can have both positive and negative environmental effects. The study challenges the conventional view of excess heat as burden-free, demonstrating that this perspective can obscure its true environmental impacts and hinder the development of more sustainable district heating systems. Furthermore, the environmental benefit of excess heat decreases as the environmental impact of the primary heat supply decreases, underscoring the importance of continuous environmental impact evaluations. Overall, this research provides a nuanced understanding of excess heat's environmental impact and offers a methodology for more informed decision-making in district heating system planning. By acknowledging and evaluating the environmental impacts of excess heat, policymakers can make more strategic decisions to enhance the sustainability of district heating systems.

Preface

This report is a Master's Thesis by Mathias Gustavsen, Magnus Slifsgaard Mikkelsen and Frederik Luft gen. Plaisier and completed during their studies in the Environmental Management and Sustainability Science program at Aalborg University. The work was conducted from February 1st, 2024 to June 7th, 2024.

This report focuses on identifying the environmental impacts of utilising excess heat in the district heating system of Aalborg municipality. Various district heat suppliers have been modelled using life cycle assessment, employing different definitions of excess heat and allocation methods to analyse the impact on the environmental footprint of the district heating system.

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Reading guide

The citations in this study follow the format (author(s), year). One interview was conducted during the study, and a summary can be found in Appendix A. This appendix will also serve as the reference for the interview throughout the study.

Abbreviations

The key abbreviations frequently used in this study are listed below:

Attributional life cycle assessment - (ALCA)

Carbon Dioxide-equivalents - (CO_2-eqs)

Combined heat and power - (CHP)

Consequential life cycle assessment - (CLCA)

District heating - (DH)

District heating systems - (DHS)

European Union - (EU)

Greenhouse gases - (GHG)

Life cycle assessment - (LCA)

Power-to-X - (PtX)

Techno-institutional complex - (TIC)

Contents

1 Excess heat potential

The European Union (EU) has a goal of reducing its greenhouse gas (GHG) emissions by 55% compared to 1990 by 2030, as well as becoming climate neutral by 2050 [European Commission, 2023]. The production and use of energy account for more than 75% of the EU's GHG emissions, making the transformation of the energy system a key factor in achieving these goals [ibid.]. One way of lowering the emissions of the energy sector could be through utilising the existing heat that is produced, but not used. This heat is often referred to as excess heat, surplus heat, waste heat, etc., but for this paper, the term excess heat will be used. As the term excess heat can have multiple definitions, this paper defines it as heat that is produced as a byproduct, which would be unused if not utilised in a district heating system (DHS). This excess heat can come from many sources. Mathiesen et al. [2023] assessed the potential of excess heat from industrial processes, wastewater treatment plants, food retail stores, metro stations, and data centres, in the 27 member countries of the EU as well as the United Kingdom. The study showed a total potential of 1.408 TWh pr. year, which is 44,3% of the total heat demand of 3.175 TWh in 2015 [Fleiter et al., 2017]. Another study that focused on excess heat from waste incineration, thermal power generation, and industrial excess heat estimated that the total excess heat is 2.858 TWh pr. year, which would be 90% of the total heating demand in the 27 member countries of the EU as well as the United Kingdom [Connolly et al., 2013]. The main benefit of utilising this excess heat would be that the excess heat could replace some of the existing production of heat, thus potentially lowering the total environmental impact of the EU's heat production.

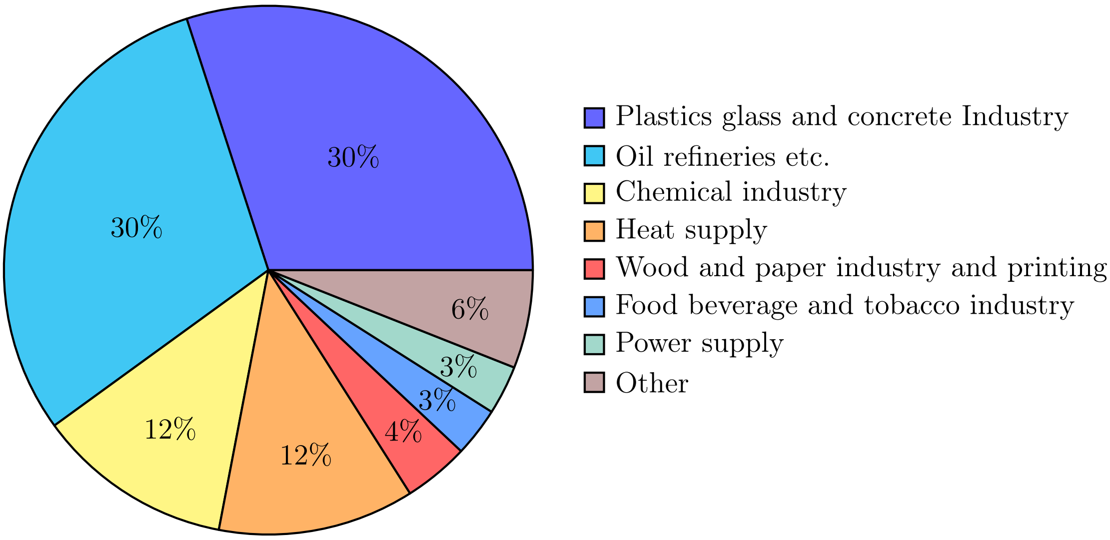

Figure 1.1. Pie chart representing the share of excess heat from different industries in Denmark [Energistyrelsen, 2023].

Although the potential for utilising excess heat is large across all the countries mentioned previously, this paper focuses on the use of excess heat in Denmark. Similar to the EU, Denmark has a goal of achieving a 70% reduction in GHG emissions by 2030 compared to 1990, as well as becoming climate neutral by 2050 [Mathiesen et al., 2021]. The excess heat potential in Denmark from sources such as industrial processes, wastewater treatment plants, food retail stores, metro stations, and data centres, is estimated to be around 18 TWh pr. year [Mathiesen et al., 2023], while the total heat demand in Denmark has been assessed to be around 51 TWh [Connolly et al., 2013]. The share of excess heat supplied by different industries as of 2022 can be seen in Figure 1.1. When looking at excess heat from sources such as waste incineration, thermal power generation, and industrial excess heat, the potential is estimated to be around 39 TWh per year or 77% of the total heating demand [ibid.]. Thus the potential for utilising excess heat is clear and well-documented, both on an EU level and on a national Danish level. In Figure 1.2 the share of used and unused excess heat in Denmark can be seen [Ramboll, 2022].

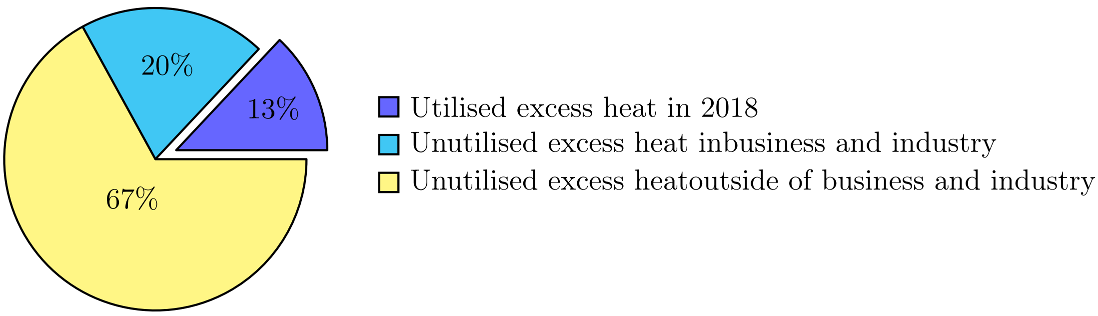

Figure 1.2. Pie chart representing the share of used and unused excess heat [Ramboll, 2022].

When looking at excess heat, it is necessary to also look at district heating (DH), as it is this technology that enables excess heat to be utilised on a large scale [Mathiesen et al., 2023]. A district heating system (DHS) allows for heat that is produced in one or more locations, to be distributed in the form of water through pipes, to be used in areas where it is needed, such as buildings within cities [State of Green, 2018]. Connecting heat producers and heat consumers through a DHS is one way that allows for excess heat to be used, and the establishment and expansion of DHSs are therefore necessary for enabling the utilisation of excess heat [ibid.]. It is estimated that 13% of the current European heating infrastructure is comprised of DH [Mathiesen et al., 2023]. In Denmark, this number is estimated to be about 50%, showing that there is a large potential for utilising excess heat in Denmark, utilising the current DH infrastructure [ibid.]. The Danish government have monitored the total amount of excess heat used in Denmark between 2020 and 2022, showing that 1,42 TWh of excess heat was utilised in 2022 [Energistyrelsen, 2023]. This number is significantly lower than the estimated potential for excess heat in Denmark, showing that there are vast amounts of wasted heat that are not being utilised. It can be difficult to pinpoint exactly why this potential excess heat is not being used in Denmark, however, sources point to a few key barriers, such as the tax on excess heat and the administrative work that is involved in supplying excess heat [Ramboll, 2022], [Fjernvarme, 2020].

1.1 Definitions of excess heat in Danish regulation

Excess heat is mainly covered by two regulations in Denmark, the Heat Supply Act Ministry of Climate, Energy, and Utilities [2024] and the Excess Heat Regulation Ministry of Climate, Energy, and Utilities [2023]. Excess heat is not defined in the Excess Heat Regulation, but it is defined in the Heat Supply Act. The Excess Heat Regulation primarily concentrates on various aspects of the price ceiling rather than the overall aspects of excess heat.

The purpose of the Heat Supply Act is to promote the most socio-economically advantageous, including environmentally friendly, use of energy for heating buildings and supplying hot water, and within these frameworks, to reduce the energy supply's dependency on fossil fuels [Ministry of Climate, Energy, and Utilities, 2024]. In this excess heat is defined as the following: "*Unavoidable heat produced as a byproduct from industrial or electricity production plants or in the tertiary sector, which would be released unused into the air or water without access to a district heating system*" [Ministry of Climate, Energy, and Utilities, 2024]. Due to this definition, excess heat is often considered environmentally neutral since it is an unavoidable byproduct that would be produced regardless and typically released into the air without being used.

As mentioned earlier, the Excess Heat Regulation mainly focuses on the price ceiling regarding excess heat. Section 1 in the regulation states the rules concerning a price ceiling for excess heat, applicable when the facility utilising and supplying excess heat has a capacity of 0.25 MW or more [Ministry of Climate, Energy, and Utilities, 2023]. This price ceiling is, according to Section 2, determined every year based on Paragraphs two and three. Paragraph two states that the price ceiling is determined as a simple average of the total production costs for heated water produced from a wood chip boiler and for heated water produced from an air-source heat pump. Paragraph three defines how the calculations for the production costs are specifically performed [Ministry of Climate, Energy, and Utilities, 2023].

1.2 Environmental impact of excess heat

Although often presented as a key part of the solution to lowering the European and Danish CO_2-emissions, the environmental impact of utilising excess heat is not a key part of the current studies on the subject [Mathiesen et al., 2023], [Mathiesen et al., 2021]. As the potential for utilising excess heat on a European and Danish level is so significant, and there is an increasing focus on excess heat utilisation, this paper seeks to explore the actual environmental impact of utilising excess heat in DHSs. Focusing on the environmental impact of excess heat can give a more nuanced view of how the future heat supply should be planned, as well as highlight how utilising excess heat can have a positive or negative impact on the environment.

As such, the following chapter contains a literature review aiming to investigate how the environmental impact of excess heat is studied in the current academic literature.

Literature review 2

The purpose of this section is to showcase the current state-of-the-art in the field of assessing the environmental impacts of excess heat in DH. Drawing upon the discoveries from Chapter 1 and the chosen articles in Section 6.1, this state-of-the-art literature review aims to pinpoint and evaluate the existing scientific literature and see how environmental impacts from using excess heat in DH are assessed in the literature, as well as identifying potential knowledge gaps that can help to form the rest of the study.

53 relevant articles were identified through a systematic literature search, which is explained further in Section 6.1, and this chapter will focus on these 53 articles. All 53 articles focus on excess heat in DH, and all do to some extent assess the environmental impacts of the DHSs with or without excess heat included. The articles are grouped into four different themes, which are the following: Review articles, Life cycle assessment (LCA), CO_2-factors and others. This division is based on a rough initial idea, regarding what primary methods are used in each article to assess the environmental impacts from excess heat in DH.

To extract the relevant information from the articles, an analysis structure is created. This structure consists of guiding questions, that when answered, will help clarify the main question of the literature review, *How does the current literature assess the environmental impact of excess heat used in DH?*. Three main questions are formulated to help reach the goal of this literature review:

1. How much of a focus is excess heat in the article, and how is it defined?
2. How does the article calculate or assess the environmental impact in the article, and which circumstances are shaping the study?
3. What is the environmental impact of using excess heat, and which factors are the cause of this impact?

These questions shape the analysis of the articles but have different scopes depending on which type of article they are applied to.

2.1 Review articles

The first group of articles to be analysed are the review articles. These articles create an initial overview of the relevant literature in the field, as well as an overview of the main problems and knowledge gaps that have already been defined and analysed. This creates a solid foundation for the further analysis of the three remaining groups of articles. Three review articles have been identified.

The first article from Gjoka et al. [2023] focuses on fifth-generation DH, meaning DHSs that can provide heating and cooling while operating at a near ambient temperature [ibid.]. This allows for an increased utilisation of low-grade waste heat. With excess heat not being the primary focus of the review article, there is no clear definition of the term, however the terms *industrial waste heat* and *urban excess heat* are both used [ibid]. The review article does not go into detail regarding how the current literature assesses the environmental impact of using excess heat in fifth-generation DHSs but concludes that there is no study containing a detailed model that includes mass flow, network pressure drops and temperature distribution, while also accounting for an LCA of the DHS [ibid.]. The article further states that future research should focus on the environmental performance of the fifth-generation DHS from a life cycle perspective, to show the potential of these systems for reaching decarbonisation targets as well as other environmental targets [ibid.]. Although not a review article, the paper from Bartolozzi et al. [2017] contains a comprehensive literature review on DHS studies. The article states that the use of LCA as a method of assessing the environmental impact of DHSs can be used to provide a more comprehensive perspective, as it can be used to evaluate a range of environmental impact categories [ibid.]. This is opposed to the traditional assessments of the environmental performance of energy systems that often only look at climate change [ibid.]. The article goes on to state that LCA studies on DHSs rarely take into account the impacts of the infrastructure of the system, concluding that only a few authors have assessed the environmental impacts of the whole energy chain from thermal energy production to DH distribution in buildings [ibid.]. In Werner [2017] the author presents the global status for DH and cooling in 2017, focusing, among other aspects, on the environmental context. Here, the author states that heat recycling generates no marginal emissions, meaning that substituting the traditional fossil energy supply with recycled heat that would otherwise be wasted, results in a decrease in CO_2 emissions [ibid.]. When estimating the emissions from the DHS, the article presents two allocation rules. The first rule being that the loss of electricity generation from steam power processes, as a result of using recycled heat, is allocated to the recycled heat [ibid.]. The second rule was that no CO_2 emissions were allocated to heat recycled from waste incineration, industrial processes and fuel refineries. The author describes this second rule as being used to not contradict the polluter pays principle [ibid.]. Lastly, the author concludes that the potential for lowering CO_2 emissions by utilising recycled heat in DHSs has been an overlooked element in contemporary climate change mitigation assessments such as the reports from the Intergovernmental Panel on Climate Change (IPCC) [ibid.].

The findings from these articles show that there is, and has been, a lack of a focus on the holistic assessment of the environmental impacts of DH and the use of excess heat. This is despite a large focus on the environmental benefits that DH and excess heat would contribute.

2.2 Articles assessing environmental impacts using Life Cycle Assessment

Inclusion of excess heat

All ten articles have in common that they do to some extent mention excess heat either by saying excess heat or waste heat. There is, however, a difference regarding to what degree each article focuses on excess heat. Articles such as [Famiglietti et al., 2021], [Diaz et al., 2020], [Feofilovs et al., 2019] and [Bartolozzi et al., 2017] only mentions excess heat in the form of waste heat a few times. In [Diaz et al., 2020] excess heat and waste heat are mentioned one time each, [Bartolozzi et al., 2017] mentions waste heat two times, in [Famiglietti et al., 2021] waste heat is mentioned three times and lastly in [Feofilovs et al., 2019] excess heat is mentioned five times. These four articles mention excess heat or waste heat the least amount of times of the ten articles on this theme. When looking at the other five articles that are left, [Mahon et al., 2022], [Pakere et al., 2023a], [Sacchi and Ramsheva, 2017], [Ivner and Viklund, 2015] and [Wahlroos et al., 2018], then the amount of times that excess heat or waste heat is mentioned takes a jump upwards. Mahon et al. [2022] mentions it 32 times, [Pakere et al., 2023a] 59 times, [Ivner and Viklund, 2015] 80 times, [Sacchi and Ramsheva, 2017] 87 times and [Wahlroos et al., 2018] mentions waste heat 200 times and excess heat four times. It can therefore be derived that there are major differences regarding how much focus is on excess heat or waste heat in each article.

Definitions of excess heat

As can be seen in the section above there is a difference regarding what words are used for excess heat. In the articles Famiglietti et al. [2021], Pakere et al. [2023a], Bartolozzi et al. [2017] and Mahon et al. [2022] the word *waste heat* is only used, and Feofilovs et al. [2019], Sacchi and Ramsheva [2017] and Ivner and Viklund [2015] only uses the word *excess heat* and the articles Diaz et al. [2020] and Wahlroos et al. [2018] uses both the words waste heat and excess heat. This section will look at how the ten articles define excess heat or waste heat.

The following articles Famiglietti et al. [2021], Diaz et al. [2020], Bartolozzi et al. [2017] and Mahon et al. [2022] do not have a specific definition of excess heat. This is even though that Mahon et al. [2022] mentions waste heat 32 times. For the other two articles, this could be because excess heat doesn't have a big focus, and is only mentioned very few times in the articles, and therefore it is not necessary to define it. In Pakere et al. [2023a] waste heat is defined either by being high temperature or low temperature, and there being different types of waste heat. In Pakere et al. [2023a] two different waste heat sources are used: waste heat from wastewater treatment and waste heat from flue gasses. Besides differentiating between high and low-temperature waste heat and the two types, then it is also shown in Figure 1 in Pakere et al. [2023a] that waste heat should be the heat source that is prioritised most out of all heat-producing methods. As with Pakere et al. [2023a] then waste heat is defined by the temperature in Wahlroos et al. [2018]. But this is just one aspect in Wahlroos et al. [2018] because in this article there is differentiation between different qualities of waste heat. The quality of the waste heat is dependent on what temperature the waste heat is being supplied and also how stable the supply is. If the temperature is high then the quality of the waste heat will also be high. Wahlroos et al. [2018] also looks into two different applications for utilising the waste heat: own consumption and external processes. Regarding own consumption then space heating is the most common use, but a challenge is that the demand for space heating is seasonal. Another use could be to use it as domestic hot water. Here the demand is more constant throughout the year. Another way in which Wahlroos et al. [2018], Ivner and Viklund [2015] and Feofilovs et al. [2019] define the waste heat is based on where the waste heat originates from. The three articles focus on industrial waste heat, Wahlroos et al. [2018] focuses on waste heat from data centres, while Feofilovs et al. [2019] has a more general approach to industrial waste heat and Ivner and Viklund [2015] has a system perspective to waste heat in DH. In both Ivner and Viklund [2015] and Sacchi and Ramsheva [2017] it is stated that the global warming potential for excess heat is allocated zero emissions in the LCA, which means that in these two articles, excess heat is seen as a *"free"* resource or as carbon neutral from an environmental point of view. Sacchi and Ramsheva [2017] also introduces the definitions *false* and *true* excess heat. *False* excess heat means that additional fuels are used to produce excess heat, and thereby it becomes *false* excess heat because it is produced on purpose. With *true* excess heat no additional fuels are used purposely to produce excess heat.

The criteria for the Life Cycle Assessments

This section will look into how the ten articles calculate the environmental impact of excess heat in DH. All ten articles are LCA studies and therefore they use this method to analyse the environmental impacts of excess heat. However, there are some differences in the approaches to the LCAs in the articles.

One aspect in which the articles differ from each other is in terms of the impact categories that are assessed.

Impact category/Article	Famiglietti	Pakere	Wahlroos	DiazFabian	Feofilovs	Mahon	Ivner	Sacchi	Bartolozzi	Jeandaux
Climate change/global warming potential	x	x	x	x	x	x		x	x	x
Greenhouse gas emissions							x			
Ozone depletion	x	x		x	x				x	x
Ionizing radiation	x	x		x					x	x
Ionizing radiation E (interim)									x	
Photochemical ozone formation	x								x	x
Particulate matter	x								x	
Human toxicity					x	x				
Human toxicity, non-cancer	x								x	
Human toxicity, cancer	x								x	
Acidification	x				x				x	x
Eutrophication					x	x				
Eutrophication freshwater	x								x	x
Eutrophication marine	x								x	x
Eutrophication terrestrial	x								x	x
Ecotoxicity freshwater	x									
Land use	x								x	
Water use	x								x	
Resource use, fossils	x									
Resource use, mineral and metals	x									
Mineral, fossil & ren resource depletion									x	
Carcinogens		x		x						
Non-carcinogens		x		x						
Respiratory inorganics		x		x						x
Respiratory organics		x		x						
Aquatic ecotoxicity		x		x					x	
Terrestrial ecotoxicity		x		x						
Terrestrial acid/nutr		x		x						
Land occupation		x		x						
Aquatic acidification		x		x						
Aquatic eutrophication		x		x						
Non-renewable energy		x		x						
Mineral extraction		x		x						
Abiotic depletion					x					
Fossil fuel depletion						x				
Number of impact categories	16	15	1	15	6	4	1	1	16	9

Figure 2.1. Impact Categories covered by the LCA-related articles

In Table 2.1 above the different impact categories that are used in each article can be seen. Several impact categories are addressed consistently across all of the ten articles. This includes the impact categories Climate Change/Global Warming Potential, Ozone Depletion, Human Toxicity, Eutrophication, Acidification, Ecotoxicity (both freshwater and terrestrial), and Resource Use (both fossils and minerals/metals). The articles Famiglietti et al. [2021] and Bartolozzi et al. [2017] includes the most impact categories with 16 each and Diaz et al. [2020] and Pakere et al. [2023a] both look at the same 15 impact categories, while Famiglietti et al. [2021] mostly looks at different ones than Diaz et al. [2020] and Pakere et al. [2023a]. Then in the middle there are Feofilovs et al. [2019] and Mahon et al. [2022] with six and four impact categories, and in the articles with the least amount of impact categories are Wahlroos et al. [2018], Ivner and Viklund [2015] and Sacchi and Ramsheva [2017] where they both only look at one impact category, climate change and GHG emissions. As can be seen in Table 2.1, then are some impact categories only addressed by a few articles. This could indicate variability in the extent to which different articles cover certain environmental impacts. For example, while Climate Change/Global Warming Potential and Human Toxicity are addressed by nearly all articles, then impact categories like Land Use, Water Use, and Carcinogens have less coverage.

Another aspect is the system boundaries of the LCAs in the articles. Whilst they are dependent on case and methods it is possible to see more commonly used approaches and some individual ones, this is covered in the following. The articles set their boundaries in different ways depending on the assessment. Cradle-to-cradle solutions have not been seen. The articles by Bartolozzi et al. [2017], Famiglietti et al. [2021], Jeandaux et al. [2021] use cradle-to-grave system boundaries in the LCAs, while Mahon et al. [2022] use a cradle-to-gate approach. Mahon et al. [2022] argues the disposal phase is to be excluded due to probable future advancements in the field during the lifetime of the system. Other articles only focus on the assembly and operations stages, this applies for Pakere et al. [2023a], Feofilovs et al. [2019] and Diaz et al. [2020]. The research of Ivner and Viklund [2015] focuses exclusively on the impacts within the operations phase of a DH system, specifically the energy production, fuel extraction, mix of fuels in summer and winter and the sources of the excess heat.

In conclusion, it can be stated that the ten articles cover a wide range of impact categories, reflecting the different focus points of each article and also the diverse environmental impacts associated with doing LCAs including excess heat in DH. It can also be concluded that the articles use different system boundaries in the LCAs, with cradle-to-grave being the most used approach.

Findings of the articles

[Famiglietti et al., 2021] investigated two scenarios: one representing the present conditions and another projecting into the future. Despite higher current CO_2-eq emissions from DH compared to heat pumps (208 vs. 118 g CO_2-eq/kWhth), the findings suggest that DH could potentially have nearly equivalent climate change impacts in the future. This potential is attributed to the integration of renewable sources, feasible with the 4th generation of DHSs. In the 2030 scenario, the CO_2-eq emissions for DH and vapour compression heat pumps were measured at 89 and 81 g CO_2-eq/kWhth, respectively. However, weighting results indicate a better environmental profile for the DHS in both scenarios, with reductions of 67% (present) and 19% (future) compared to heat pumps.

The article Pakere et al. [2023a] examines the potential for eliminating fossil fuels in heat supply systems, particularly in multi-source DH. Two waste heat sources, sewage water from municipal wastewater treatment plants and deep cooling of flue gases, are used as scenarios and evaluated for heat production via heat pumps. These are then compared with the current situation. The results indicate that integrating waste heat from sewage water and flue gases, coupled with heat pumps, could replace natural gas for peak load coverage. Environmental impact assessments reveal that implementing a low-temperature DH scenario yields the lowest environmental impacts, while biomass heat production remains a significant contributor across all scenarios, integrating more heat pumps could further reduce environmental impacts.

Wahlroos et al. [2018] has a different focus than the other articles. In this article waste heat utilisation emissions are assessed through two methods: consequential life cycle assessment (CLCA) and attributional life cycle assessment (ALCA). The study concludes that the CLCA method appears to be more effective in assessing the impact on CO_2 emissions within a DHS compared to ALCA.

The article Diaz et al. [2020] focuses on two scenarios, one baseline scenario and one future. The study wants to assess the environmental impacts of transitioning from the current 3rd generation DHS in the Gulbene region to a 4th generation low-temperature DHS. Results from the LCA indicated positive benefits across most impact categories, except for mineral extraction, which showed a negative impact due to the energy increase from extractive activities required for building refurbishment. Implementing low-temperature

DHSs, primarily powered by renewable energies like biomass, was found to reduce fuel consumption and environmental damage, particularly in parishes where thermal energy is sourced entirely from renewable energy sources. However, building refurbishment activities, especially in areas with poor insulation, could result in significant environmental impacts, potentially outweighing the benefits of DHS construction, particularly in parishes where 3rd generation DHSs are already operational.

In Feofilovs et al. [2019] four scenarios for upgrading an existing DHS and introducing a low-temperature DHS with solar photovoltaics (PV) were assessed. The study found that modernising the boiler house would notably lower the environmental impact of the DHS. The scenario combining low-temperature district heating (LTDH) and solar PV showed the best results. However, implementing LTDH alone didn't yield significant improvement. DH operation, especially heat production and ash treatment, had the most environmental impact. The study also stated that future LTDH designs should consider additional low-temperature sources like solar thermal collectors and heat pumps.

Three scenarios were assessed and compared in Mahon et al. [2022]. One looking at a waste heat-fed heat pump, and another looking into a biomass-based combined heat and power plant with a conventional gas boiler. The study found that DHSs, particularly biomass combined heat and power (CHP), have lower environmental impacts than individual gas boilers. Biomass CHP DH showed the lowest impact, but water-source heat pump DH was near this when considering 2030 electricity data. DHSs can significantly reduce GHG emissions but have higher human toxicity potential due to infrastructure construction. Biomethane usage could cut emissions by at least 11,4%. Biomass CHP DH is recommended for heating South Dublin County Council buildings, with potential fossil fuel reductions of 73%, while water-source heat pump DH could reduce it by at least 47%. The article also concluded that promoting DH requires legislative support and stakeholder engagement and that future studies could explore indicators like particulate matter and urban biomass combustion.

Six different scenarios were investigated in Ivner and Viklund [2015]. Scenario A: Summer production with a heat-only boiler, no electricity substitution. Scenario B: Summer production with CHP, substituting with Nordic mix electricity in winter. Scenario C: Summer production with CHP, substituting with EU marginal mix electricity in winter. Scenario D: Winter production with CHP, substituting with Nordic mix electricity in summer. Scenario E: Winter production with CHP, substituting with EU marginal mix electricity in summer and last scenario F: Year-round production with CHP, substituting with Nordic mix electricity in both seasons. The study revealed that utilising industrial excess heat in DHSs impacts GHG emissions differently based on heat production type and analysis boundaries. Heat-only boiler systems show GHG reduction, while CHP systems' impact varies, depending on factors like lost electricity valuation.

The article Sacchi and Ramsheva [2017] was the study that looked into the most amount of scenarios of the ten articles, with ten scenarios being assessed. The study found that Aalborg's price ceiling for DHS users restricts excess heat recovery investment, thereby limiting carbon footprint reduction potential by up to 93%. However, it keeps end-user prices low. Aalborg's transition scenarios, particularly scenario 9, demonstrate a significant reduction in heat carbon footprint (from 153 to about 11 kg CO_2-eq. per GJ) by increasing excess heat share to 90% of the supply mix.

Four different scenarios were investigated in Bartolozzi et al. [2017]. Two benchmarking scenarios with natural gas as a fossil fuel, one with centralised heating and cooling via DH and the other with individual boilers and air-air heat pumps in each home. The other two scenarios use renewable energy sources, one scenario looks at geothermal and the other at biomass. The study found that DHSs, especially when combined with renewable energy sources, can reduce carbon footprint and resource depletion. Operational stages, particularly electricity consumption and biomass production, exert the most significant environmental impact. Assembly stages, involving metal components in construction, also contribute significantly [ibid]. In the article, it is further stated that the analysis shows that climate change, often considered to be a significant proxy for environmental impacts, only provides partial information for assessing the environmental performance of the different scenarios. The authors further state that while the geothermal and biomass DH scenarios perform better in terms of climate change compared to the benchmarking scenarios, they may have even greater impacts in some impact categories, such as particulate matter and terrestrial eutrophication [ibid.]. The authors also state that further research is needed to quantify potential advantages, evaluate alternative system configurations, and compare results across different climates.

Jeandaux et al. [2021] identifies a gap of literature in the field of assessing DHS's environmental impacts apart from reductions in CO_2 emissions. The article mentions that biomass, for example, can be a trade-off between reductions of CO_2 emissions and increased emissions of particular matter. Based on that, the article aimed to step into that gap by including other life-cycle environmental impacts in several European scenarios of DHSs. An added factor is density due to which there were four regionally differing DHS environments assessed, each with a dense and less dense version, leading to eight scenarios overall. The assessment covers all life cycle steps: production, distribution, installation, use/maintenance and end-of-life specifying "waste collection", "transportation" and "landfilling". The system boundaries defined for the individual systems cover the low-pressure distribution of natural gas and low-voltage electricity networks. Whilst mainly focusing on geothermal potentials, it also includes the currently dominant forms of DHSs in European countries in its scenario considerations and differing energy mixes. Their findings emphasized the importance of waste heat utilisation for efficiency gains as well as cogeneration. Herein they stress the importance of proper waste heat accounting and cogeneration allocation as EU directives clarify rules for it but practice is yet to catch up. Even though the main focus of the article was the geothermal technology application, a lot of the findings and discussion points can be contextualized in the bigger scope of DHSs and the potential for waste heat usage. Combined with the criticism on environmental impacts not being assessed in related literature and their methodological approach there are points other articles only touch upon which this article adds to the discourse. These are the importance of assessing more impact categories and their potential interrelation depending on the technologies and fuels used, especially in the case of biomass. For biomass, there is a recommendation to challenge the carbon-neutrality assumption that other articles often make. Jeandaux et al. [2021] does not only put special emphasis on biomass fuels, but they also recommend conducting time-dependent LCAs to assess yearly fluctuations in environmental impacts. Lastly, whilst not being done in the study at hand, there is an emphasis expressed regarding "*dynamic or at least seasonal data*" being preferable to annual average data for heat generation and demand to have detailed inventories and thus better information on the environmental impacts.

Summary

A varying degree of focus on the topic of excess heat can be seen in the ten analysed articles, with some articles including it as the main focal point of the study, while other articles include it as a small part of certain scenarios. Furthermore, there is a large variance in how the concept of excess heat is defined throughout the articles. While some articles do not define the term, it is commonly defined based on the source of the excess heat, the temperature and the internal or external use of the heat.

A variance can also be seen in the scope of the LCA studies. In terms of the environmental impact categories, Climate change and Human toxicity are commonly included in the studies, while categories such as Land Use, Water Use and Carcinogens are less frequently included. The system boundary of the LCA is another aspect in which the articles differ from one another. A few articles use a cradle-to-grave approach, while other articles argue for the exclusion of the disposal phase due to possible future advancements. It can also be seen that some articles have more limited system boundaries, only including the operations or assembly and operations phases of the studied system.

In general, the LCA studies show that the use of excess heat can help minimise the environmental impact of DHSs, especially in terms of CO_2-emissions. However, negative environmental impacts can also be seen when looking at a broader scope of impact categories. Negative impacts are shown in terms of mineral extraction, human toxicity potential, particulate matter, and terrestrial eutrophication. The need for assessing a broader scope of environmental impact categories, to gain better results is also a recurring point in the articles. Another recurring conclusion is the fact that the system boundaries and the scope of the LCA will have a big impact on the results, as elements such as heat sources, infrastructure, and climate can have a drastic influence. In connection to this, there is an emphasis on the need for including seasonal or dynamic aspects to the studies, to improve the quality of the findings.

2.3 Articles assessing environmental impact through CO_2-emissions

Out of the 53 articles, 33 articles consider the environmental impact by focusing on the reduction of CO_2 emissions. These articles use other methods than LCA-related practices to look into CO_2 emissions (direct and equivalents) of DHSs. In this section, the conducted methods are briefly looked upon.

All state an environmental assessment in either their title, abstract or tags. Most assess environmental aspects due to their consideration of CO_2 reductions. Different ways how the authors assess and state these (CO_2 eq, CO_2, CO_2 eq/kWh, in percentages or only in total amounts of tonnes, CO_2 emissions factor). Some are more detailed than others in their assessment of where exactly the emissions stem from within the system.

Different heat terms used in the articles

The literature used in this review uses different terms for excess heat and the meaning sometimes differs as well. Most articles use at least one of the terms listed below. Some also use more than one. Even though there are different possible definitions, some articles do not define the term that they are using and also the articles that use more than one term generally seem to use the terms without stated definitions. This issue became apparent in the initial phases of the literature review and is looked at to clarify any potential misunderstandings.

From the articles that look into primarily CO_2 reductions as an environmental impact from the utilisation of excess heat in DHSs, there were some articles which addressed the issue of defining excess heat directly:

Pettersson et al. [2020] stress the fact that they identified four terms for "*the heat discharged from an industrial process*" (the fourth here being residual heat) and use the term Industrial Excess Heat (IEH) consistently. They further differentiate between "*avoidable*" and "*unavoidable*" IEH. Avoidable here is the IEH that can be reused in its source process or avoided by changing the process without loss of product quality. The unavoidable IEH is heat that cannot be reused or reduced internally and is therefore an inevitable byproduct of the industrial process. They also acknowledge that the separation can be case-specific and also depends on other factors like investment performance criteria to be categorised as either avoidable or unavoidable. Morandin et al. [2014] picks up the aspect of avoidability by stating what is normally regarded as waste heat can often be partially recovered by "*proper retrofit of the heat recovery and utility systems*" and that "in practice, there is always an excess of heat available from a process due to non-ideal heat recovery and that such heat is often at sufficiently high temperature to be used internally or to be exported at least as DH".

In the case of the Latvian DH-sector Latõšov et al. [2022] present different possible definitions for "*waste heat*" that a DHS can utilise from outside sources like industrial plants. "*Waste heat*" here refers to unused thermal energy released during production processes, which is inevitably generated in any energy conversion. Repurposing waste heat for heating or water heating can increase efficiency and reduce pollution. Here they are pointing out a problem to define what exactly stays dissipating heat and which part of it becomes "*useful*" heat again through a recovery process and thus increasing efficiency. This waste heat, and also waste cooling, can be defined as a byproduct of industrial processes or energy facilities and requires systems like DH to prevent it from dissipating unused into the environment.

Olsson et al. [2015] also works with excess heat in the context of cogeneration and the

Term	Number of articles
Waste heat	18
Excess heat	7
Industrial excess heat (IEH)	6
Surplus heat	2

Table 2.1. Number of articles that use each of the four identified terms for excess heat

struggle to clearly define it drawing from a lot of different sources themselves. They further contextualise the issue with the existing EU policies and regulations. The energy efficiency directive specifically supports and encourages the practice of cogeneration, where heat from the same process that is used for electricity production is making use of the cogenerated heat [EU, 2023]. If the residual heat from industrial processes is not recovered and reused Olsson et al. [2015] identifies it as excess heat which can exist in many forms and at different parts of the industrial processes at hand. The exact definition in that article for excess heat stems from the Swedish Energy Agency (SEA), stating it to be "*Excess energy that cannot be utilised internally and where the alternative is that the heat is released into the surroundings*" [Olsson et al., 2015].

Morandin et al. [2014] define industrial excess heat to be "*heat at medium-low temperature that is not used in industrial processes and that is normally dissipated to the environment*". They and Kauko et al. [2017] address that excess heat can exist at different temperatures which presents different challenges for the recovery and utilisation of it. Broberg Viklund and Johansson [2014] defines industrial excess heat as "*heat generated as a by-product of industrial processes. This heat is not used today, but could be used to create benefits for the industry and the society*". These different challenges and possibilities from different sources of excess heat make for a variety of technologies that can be used in the process of integrating that heat into DHSs.

It can be summarised that while it seems to not exactly matter what is chosen for the heat term. It rather needs to be identified if and how the heat can be utilised and what is the most feasible and beneficial way for industry and society. Especially with the EU identifying DHSs and excess heat utilisation as necessary and pursuable, this field which has the technological means, becomes increasingly wider in its integration of utilising the heat unused in its primary processes. The beneficial environmental impact of utilising excess heat is often stated in the literature and also the goals of the EU. How these impacts are calculated and assessed will be presented next.

How is the environmental impact of excess heat calculated?

This section looks at how the articles that only look at the environmental impact in terms of GHG- or CO_2-emissions, calculate this impact.

Overall, there are many similarities between the articles in the approach they have taken to calculate the CO_2-emissions of using excess heat in a DHS. One of the most common methods seems to be an approach to calculate the environmental impact in terms of the CO_2-emissions saved from the avoided use of fossil fuels as a result of using excess heat. An example of this can be seen in Kim et al. [2017], where the authors calculate the avoided emissions from the fossil fuels bunker c fuel oil, and liquefied natural gas, using emissions factors from the 2006 IPCC guidelines. Similar examples to this can be seen in Dou et al. [2018], Egging-Bratseth et al. [2021], Karner et al. [2018], Kauko et al. [2018], Morandin et al. [2014], Jönsson et al. [2008] and Brange et al. [2016]. Emissions factors were often found for the specific country that the case was being studied in, e.g. Dou et al. [2018] uses Japanese emission factors while Egging-Bratseth et al. [2021] uses Norwegian factors. However, other articles used unspecified or default values for the CO_2-emission factors Zivkovic and Ivezic [2022], Brange et al. [2016]. Some articles, such as Kim et al. [2017], have a very simple approach to calculating the CO_2-emissions from using excess heat, only taking into account the saved emissions from the avoided use of other heat sources. However, articles such as Sandvall et al. [2015] also take into account other factors such as the transport system and the long-term marginal electricity generation. Another example can be seen in Zivkovic and Ivezic [2022] where the authors take into account the emissions that occur during the extraction, processing, storage, transport and combustion of the fuels. Karner et al. [2018] also takes the emissions from the electricity needed for running heat pumps into account. Broberg Viklund and Johansson [2014] look at the emissions impact when excess heat is used to produce electricity, resulting in the marginal electricity producer reducing its production. As such, the emissions can be calculated based on the avoided production.

One article, Kohne et al. [2021], tries to develop a time-dependent method for continuously evaluating CO_2-emissions in an industrial heating network. In this method, they take into account the emissions from the energy converters, such as a CHP plant and the emissions from the waste heat sources [ibid.]. This article stands out from the rest, in that it focuses on how the CO_2-emissions vary over time as a result of using excess heat. This is in contrast to a majority of the other articles, that include the time aspect in their analysis, but mostly in terms of modelling how the heat demand or supply changes over time.

A majority of the articles view the use of excess heat as emission-free, however, some articles also included potential emissions that could occur as a result of using excess heat. Pettersson et al. [2020] distinguishes between avoidable and unavoidable excess heat. For avoidable excess heat, meaning excess heat that could instead be used internally at the source, the emissions from the heat-producing activity are allocated to the excess heat [ibid.]. In this case, the emissions from the natural gas boiler are calculated using emission factors and allocated to the excess heat. If the excess heat instead was unavoidable, no emissions would be allocated. Another example is in the article from Dou et al. [2018] where the emissions from construction of infrastructure and electricity consumption were subtracted from the saved emissions of the substituted fuel. Morandin et al. [2014] allocate the emissions from the avoidable fuel to the excess heat.

Although these articles all look at the CO_2-emissions from using excess heat, the environmental assessments are often a small part of studies which often focus more on the energy-planning aspect of using excess heat. As a result the economic and technical aspects often dominate the content of the papers rather than the environmental considerations.

What are the circumstances for the studies

Another important aspect to consider when looking at how these articles assess the CO_2-emissions of excess heat is the circumstances and scenarios for which the emissions are calculated.

There is a large geographical variation in these articles, with studies on cases from South Korea, Japan, Denmark, Norway, Estonia, United Kingdom, Sweden, Serbia and more. Kim et al. [2017] and Kohne et al. [2021] study industrial areas and industrial excess heat, where Kim et al. [2017] focuses on the impact of substituting heat from fossil fuels with excess heat, as well as the impact of expanding the DHS into other areas. Kohne et al.

[2021] instead focuses on different consumers of the DH, such as high-temperature or low-temperature consumers and a different DHS. The impact of connecting DHSs is a common theme in the articles, with Kim et al. [2017], Kohne et al. [2021], Dominković et al. [2017], Karner et al. [2018] and Sandvall et al. [2015] all looking at this particular aspect. Other articles look at specific sources of excess heat, such as Egging-Bratseth et al. [2021] where the excess heat is delivered from an ice rink, Cowley et al. [2024] where the excess heat comes from a mine, Zivkovic and Ivezic [2022] where the excess heat is sourced from a wastewater treatment plant, Jönsson et al. [2008] who studies the impact of excess heat from Kraft pulp mills and Weinberger et al. [2017] where the heat is supplied from a steel mill. Kauko et al. [2018] and Brange et al. [2016] look at prosumer scenarios, which is a way of describing actors in a DHS that both consume and produce heat. Another aspect is whether or not excess heat is the main focus of the study, or whether it is only a small part, in the form of a single scenario. Broberg Viklund and Johansson [2014] are unique, in the sense that the article also studies the use of excess heat to produce electricity, while most other articles focus on the use of excess heat either internally or externally in a DHS. Latõšov et al. [2022] and Arnaudo et al. [2021a] are examples of articles where the focus primarily is on DH, with excess heat being a smaller part of the study.

Overall, the scenarios and circumstances for the studies found in the articles vary widely, with many different sources of excess heat, different circumstances for the use of excess heat and different boundaries for the systems being studied.

What is the environmental impact of Excess Heat

This section is guided by the question "*What is the environmental impact of using excess heat?*" to put the results and findings of the articles from the literature review into perspective. Specific focus is placed on how articles perceive excess heat utilisation to be influencing environmental impacts, by what means these are substantiated and further if there are potential negative environmental impacts.

The articles generally present DHSs and the utilisation of excess heat to have a positive environmental impact. The impacts that are evaluated, are presented as beneficial to the environment in the form of reduced CO_2 emissions either by reduced resource use or substitution of CO_2 intensive emissions. Here the utilisation of excess heat is presented as an option for substituting heat production by using already existing heat.

This reduction in CO_2-emissions can be achieved by various mechanisms, including the substitution of traditional CO_2-intensive heat sources with excess heat, efficiency improvements, and the strategic coupling of sectors to reduce fossil fuel dependence. Articles such as [Dominković et al., 2017] and [Doračić et al., 2018] underline the environmental benefits of integrating industrial waste heat into DHSs, suggesting considerable reductions in CO_2 emissions. These benefits are further improved by technological and operational enhancements, such as those discussed in [Egging-Bratseth et al., 2021], which include diversifying heat generation sources and employing demand-side management strategies. The introduction of innovative technologies, such as heat pumps highlighted in [Zivkovic and Ivezic, 2022], and the integration of waste heat, as explored by [Karner et al., 2018], are crucial for enhancing system efficiency and reducing emissions. However, the environmental performance of these technologies can vary significantly based on the available electricity mix, as indicated by the findings of [Arnaudo et al., 2021b] which state that an onsite CHP plant was less impactful than using grid electricity for heat pumps at times. The research by [Kauko et al., 2017] and [Kauko et al., 2018] demonstrates that LTDH systems, when supplied with renewable and waste heat resources, can offer reduced CO_2 emissions including enhanced efficiency. This reduction is dependent on the heat source and the operational temperatures, which directly influence the system's overall efficiency and environmental footprint. Findings by [Kim et al., 2017] and [Olsson et al., 2015] provide a broader perspective on the potential for significant CO_2 emission reductions and the importance of considering environmental labelling and market conditions in evaluating the environmental impact of excess heat in DHSs. The influence of the electricity mix, especially in the use of heat pumps and the integration of renewable energy sources, plays a critical role in determining the net environmental benefit [Arnaudo et al., 2021b]. Broberg Viklund and Johansson [2014] show that the use of industrial excess heat in DHSs reduces global CO_2-emissions in four of six scenarios, while the use of excess heat to produce electricity reduces CO_2-emissions in all scenarios. The CO_2-reduction in all scenarios for the excess heat used in electricity production is explained by the assumption that it is replacing marginal electricity production from coal or natural gas. The emissions from excess heat used in DHSs are dependent on the type of heating system it replaces. When the DHS is based on bio-heat only boiler the emissions will be reduced, however, when the system is based on bio-CHP the emissions could increase if e.g. the marginal user of biofuels is a producer of diesel and the marginal electricity production is based on coal. Similar findings can be seen in Broberg Viklund and Karlsson [2015], which shows a general reduction in emissions when utilising excess heat, however in certain scenarios the emissions will increase due to a reduction in electricity production. Pakere et al. [2023b] concludes that the highest CO_2-reduction potential can be seen in a DHS based on fossil fuels and biomass.

Considerations and Counterpoints

While the overarching narrative supports the positive environmental impact of utilising excess heat in DHSs, some nuances and conditions affect the outcome:

As shown in the findings of [Arnaudo et al., 2021b], the environmental benefits of excess heat utilisation can be influenced by the electricity mix used for heat pumps and waste heat recovery technologies. The carbon intensity of the electricity grid and the variability of market prices can make direct use of fossil fuels occasionally more favourable from a CO_2 emissions perspective. The construction and expansion of infrastructure required for integrating excess heat is discussed by [Karner et al., 2018] (see also [Mahon et al., 2022]), and create additional CO_2 emissions that need to be taken into account. The diversity of fuel types, the availability of storage technologies, and the density of the DHS significantly influence the system's flexibility, efficiency, and capacity to integrate intermittent heat sources. [Cowley et al., 2024] addresses the environmental implications of integrating unconventional heat sources like water from mining facilities and highlights the role of technological and infrastructural adaptations in maximising environmental benefits. The study from Morandin et al. [2014] shows that using excess heat in DHSs is a less beneficial option in terms of CO_2-emissions when compared with biomass boilers or CHP systems. Here, it would be more beneficial to reuse the heat internally at the source. The use of excess heat is only beneficial if the DH and heat sources are based on similar or worse technologies compared to the excess heat sources [ibid.]. Another article comparing the internal use of excess heat to the external use is from Jönsson et al. [2008], who concludes that in most scenarios external use of excess heat results in lower CO_2-emissions compared to internal use. The authors further state that while external use of excess heat is more beneficial in terms of lowering CO_2-emissions, it is often not the most beneficial option from an economic point of view [ibid.].

The stated articles focused on environmental impacts almost exclusively through the means of evaluating the amount of CO_2-eq. reductions. This seems so far reasonable as it appears to be common practice in the field of energy-related studies and is also a defined target in the European Energy Efficiency Directive regarding DHSs EU [2023].

Summary

The environmental impacts of utilising excess heat in DHSs in regards to CO_2-reductions and the means to achieve them vary depending on the DHS, the applied technologies, fuel sources and type of grade of the utilised excess heat. The literature provides a wide range of different cases in which unutilised excess heat can be integrated into DHSs and substitute primary energy sources for heat.

Mainly the environmental impact is presented in the reductions of CO_2 by either burning less fossil fuels as they are substituted by already existing heat within the system or the substituting of CO_2 intensive fuels by less or non CO_2 emitting fuel sources.

Whilst these benefits are presented very positively in general, some authors are stating the details in the cases to be crucial to ensure optimal utilisation. Some of the articles point out that there are generally well-running scenarios but emphasise the attention to detail making a considerable difference in the outcome of emitting CO_2 emissions. So some decisions seem counterintuitive for example burning biomass directly instead of using heat pumps can be more beneficial as long as the electricity mix at the time is very fossil-fuel intensive.

2.4 Articles assessing environmental impact through multiple indicators

A fourth grouping of articles is made, based on articles that focus on a broader range of environmental impacts beside CO_2-emissions, while not using LCA as a method. In this section, the main findings from these articles are presented.

Definitions of excess heat

For this group, three articles have been identified. These are: [Lal et al., 2022], [Fang et al., 2015] and [Abdurafikov et al., 2017]. First, the number of times that excess heat has been mentioned in each article is counted, to get an idea of how much attention the topic has been given. Lal et al. [2022] mentions waste heat 47 times, Fang et al. [2015] 184 times, and Abdurafikov et al. [2017] mentions waste heat 39 times and excess heat five times. As can be seen, then there are differences regarding how many times waste heat or excess heat is mentioned in each article, indicating a varying degree of focus on the subject. The term waste heat is the most used word for defining excess heat of all the articles and excess heat is almost only used because of other studies being referred to in the articles. All three articles, Lal et al. [2022], Fang et al. [2015] and Abdurafikov et al. [2017] do not specifically define excess heat, but in Lal et al. [2022] and Fang et al. [2015] both articles say that there are different grades of excess heat (low, medium and high) based on the temperature of the excess heat are mentioned. Fang et al. [2015] and Abdurafikov et al. [2017] also mention excess heat as industrial waste heat, which is the overall focus in Fang et al. [2015] and used as a scenario in Abdurafikov et al. [2017]. Abdurafikov et al. [2017] mentions in the scenarios the term *prosumers* as the only article in this group. It is also stated in Abdurafikov et al. [2017] that DH that comes from excess heat is assumed to be renewable. Lal et al. [2022] is the only article out of the three that mentions that the excess heat reuse potential is the greatest during the winter period. This is because the demand for residential heating is the highest during this period of the year because of low outside temperatures.

How are the environmental impacts calculated

In Lal et al. [2022] an India-specific activity and emission inventory is utilised. The inventory encompasses monthly, spatially resolved (25 km $\times$ 25 km area) emissions of PM2.5, CO_2, black carbon, organic carbon, SO_2, NO_x, and total nonmethane volatile organic compounds. Major emission sources covered in the article include the following: power plants, different industries, residential biomass, open burning, distributed diesel, and transportation. Fang et al. [2015] does not include environmental aspects as such itself, but instead refers to a case study in Chifeng in northern China, where environmental aspects have been taken into account. The article uses a method, benefits evaluation, to calculate the CO_2 reductions during a heating season for the case area.

This is only a very minor part of the article, and therefore, the environmental aspect is minimal to non-existent in Fang et al. [2015]. In the article, [Abdurafikov et al., 2017], CO_2 and particulate emissions are calculated as the total amount of emissions originating from the final heat consumption of the building stock per unit of floor area. Meaning CO_2-eq and particulate emissions pr. m2 in the buildings in the studied area. The emission factors were gathered from the GEMIS database which is a global database. The article studies an area in southern Finland with around 78 thousand inhabitants. The heat in the DHS is supplied by biomass-fired CHP, as well as heat-only plants running mainly on natural gas and fuel oil. The annual fuel mix consists of 81% biomass, 15% natural gas and 4% heavy fuel oil. The article looks at five scenarios with one of them being a waste heat scenario. This scenario consists of connecting a source of waste heat to the DHS 10 years into the study's 20-year period. The waste heat is from the exhaust air of a data centre.

Circumstances for the studies

Lal et al. [2022] utilises different scenarios, a baseline year of 2015 and three future scenarios extending to 2050. The 2015 inventory utilises an engineering and technology-based approach for energy emission modelling. This approach incorporates technology parameters such as type, efficiency, specific fuel consumption, and emission factors to calculate emissions. Fang et al. [2015] takes point of departure in the city of Chifeng, a rapidly developing city in Inner Mongolia, China, which has a downtown area with a population of 700.000. The DHS covered nearly 23 million m2 in 2013 and is assumed to be increasing by 2-3 million m annually. The DH relies on five CHP plants with a capacity of 1.156 MW, meeting the peak heat demand of 50 W/m2 in January. A new district near a copper smelter is planned without conventional heat sources, which necessitates the recovery of waste heat from the smelter. The heat sources within the smelter are diverse. Using an entransy-theory-based approach, the heat collection process is optimised, resulting in the recovery of 85 MW of waste heat from various sources from the smelter, which improves energy efficiency and reduces emissions. The article Abdurafikov et al. [2017] focused on a typical Finnish area heated with DH, exploring various scenarios for its future development. By simulating different scenarios, the aim was to compare their technical performance and environmental impacts, with a focus on the demand side of the DHS and the choices made by end users. The simulations were conducted using the APROS software. The study looked into three different types of consumers based on heat load profiles: residential, office, and public buildings, and the study period covered 20 years from 2015 to 2035. The selected case area for this study corresponds almost entirely to the DHS area in the municipalities of Tuusula and Järvenpää in southern Finland. Five different scenarios were investigated in the article, and these are the following: a conservative scenario, an extensive scenario, an extreme scenario, and a utilisation of waste heat and a solar heat prosumer scenario. The scenarios that are analysed can be categorised into three groups. Firstly, there are scenarios involving decentralised heating technologies replacing DH in buildings, with varying adoption rates, the three first scenarios are conservative, extensive, and extreme. There is also a scenario involving waste heat from a data centre being utilised in the DHS. lastly, there is a prosumer scenario where heat end-users transition into heat prosumers, and thereby they act as both consumers and producers.

Findings from the three articles

The article Lal et al. [2022] says that the DHS scenario offers near zero ($<$0,04%) CO_2 emission reductions nationwide, while the organic rankine cycle scenario provided CO_2 reductions between 1,9 - 7,4% nationwide. Premature deaths due to PM2.5-related causes are substantial, with the ORC scenario consistently offering higher health benefits compared to the DHS scenario. However, effectiveness in reducing the number of deaths decreases in future scenarios due to factors like reduced residential biomass burning and an increased fossil-free energy supply. In the case of [Fang et al., 2015] during a single heating season from mid-October to mid-April (6 months), the use of excess heat of a copper smelter resulted in a reduction of CO_2 emissions by 34.857 tons, SO_2 and NO_x emissions by 113 tons and 98 tons respectively, and conserved more than 150.000 litter of water. In the article [Abdurafikov et al., 2017] it is suggested that utilising excess heat could help reduce CO_2 emissions significantly. CO_2 emissions were reduced by 50% in the case area when the share of waste heat in the supply was 20%. The article also states that the use of waste heat causes the greatest reduction in particulate emissions of all scenarios compared. Additionally, it is mentioned in Abdurafikov et al. [2017] that the utilisation of waste heat improves almost all aspects, including reducing non-renewable heat consumption.

Summary

The review of the three articles, in the Section above, looks into the concept of excess heat. Across these three articles, excess heat is mentioned in all of them, but to varying degrees, which could indicate different degrees of focus on the subject. While waste heat is the most used term in the articles, "*excess heat*" is also referenced, though often only in relation to other studies. None of the three articles offer a precise definition of excess heat, but Lal et al. [2022] and Fang et al. [2015] mention different grades of excess heat based on temperature. Additionally, Abdurafikov et al. [2017] introduces the concept of *"prosumers"* and assumes DH from excess heat to be renewable. The review also reveals differences in environmental impact calculations. But despite methodological differences, then all articles agree on the potential environmental benefits of utilising excess heat, particularly in reducing CO_2 emissions and non-renewable heat consumption.

2.5 Conclusion of the literature review regarding excess heat

This section will highlight the knowledge gaps identified in the literature review and outline the specific gaps that will serve as the focus points and foundation for the analysis of this study.

Lack of standardised definition: None of the articles offer a precise definition of excess heat, indicating a lack of standardised definition. The few articles where excess heat is somewhat defined, then these definitions often differ from article to article. This suggests a need for a universally accepted definition of excess heat to ensure consistency across studies and facilitate comparison between these.

Inconsistency in environmental considerations: There is also observed inconsistency throughout the articles regarding the depth and approach of environmental considerations both for LCA studies and non-LCA studies. While some articles utilise a comprehensive activity and emission inventories that are specific for example to the geographical area and/or technology that is being used, then others reference case studies without doing a thorough environmental analysis themselves. This indicates a gap in the depth and consistency of environmental assessments related to excess heat utilisation.

Variation in the scope of LCAs: There is considerable variation in the extent and scope to which excess heat is addressed in LCAs. Some articles focus on a broad range of impact categories, while others only consider climate change and GHG emissions. This variability suggests a need for standardisation in the scope of LCAs related to excess heat utilisation to ensure comprehensive environmental assessments.

Importance of system boundaries and scope: The importance of system boundaries and scope in LCAs is emphasised across the articles. Factors such as heat source, infrastructure, and climate can significantly impact the results of LCAs. This highlights the need for further research to refine system boundaries and scope in LCAs related to excess heat utilisation.

The temporal aspect in LCAs regarding excess heat: There is also a need to incorporate the time aspect into LCAs to provide a more dynamic perspective of the environmental impact of using excess heat over time. Only one study includes the time aspect when doing an LCA on excess heat by differentiating between the two seasons summer and winter. It could therefore be argued, that there is a gap regarding the time aspect of using excess heat in DH. The time aspect should be expanded to have a larger role when doing an LCA on excess heat utilisation in DH to fully understand the true environmental impacts of this.

All five different knowledge gaps, that are mentioned above, will in some way or another be included or taken into account in the rest of this study. A more detailed explanation regarding what extent each identified knowledge gap will be focused on is presented in Section 3.

3 Research question

As presented in Section 1 there is a significant potential for excess heat utilisation. Both at the EU and Danish levels there is a substantial potential for utilising excess heat from various sources to meet current and future heating demand. This potential is well-documented and represents a considerable portion of the total heating demand, which makes it an interesting and worthwhile subject to investigate further.

Current studies on excess heat utilisation, which were analysed in Chapter 2, often focus on the technical and economic aspects of excess heat, thereby neglecting its environmental impact. However, conducting a thorough environmental assessment is important to fully understand the benefits and drawbacks of excess heat utilisation. This will therefore be done in this study through an LCA of the DHS in the municipality of Aalborg.

Another important knowledge gap uncovered in Section 2 is the temporal aspect of utilising excess heat in DH. As explained in Chapter 1, the availability of excess heat and the DH demand fluctuates throughout the year. This aspect will therefore have a key role in the LCA that is performed in this study.

Based on the findings outlined in Chapters 1 and 2, this study seeks to address the following research question:

How does the utilisation of excess heat influence the environmental impact of the district heating system in Aalborg municipality?

3.1 Sub-questions for the study

The research question is addressed through three sub-questions outlined below. The methodological approach for addressing these sub-questions is detailed later in the research design in Section 5.

SQ 1: How can an hourly LCA model be used to support decision-making?

Based on the findings of the literature review and the apparent gap of knowledge regarding environmental impacts on a smaller timescale level than a year or heating periods (half a year). The question is formulated in regards to decision-making as insights on a more granular timescale and broadened scope surpassing the CO_2-focused majority of research is assumed to provide a better understanding of how decisions for or against technological changes in a DHS in order to fulfil the goals of EU, national and regional institutions and what implications these new insights could have for the future prospect of development.

SQ 2: How do varying definitions of excess heat affect the environmental impact associated with its utilisation in district heating systems?

This sub-question seeks to investigate how different different definitions of excess heat, that are used by different actors, affect the allocation of environmental impacts and the overall environmental impact of utilising excess heat. This is done through different scenarios in the LCA. The definitions will also be examined in relation to each other, as well as in terms of determining responsibility for the environmental impacts associated with excess heat utilisation.

SQ 3: What are the potential barriers and opportunities for minimising the environmental impact of the district heating system when utilising excess heat?

The current and future operation of the system will involve utilising excess heat on the supply side, a topic that will be explored in this sub-question. Various factors, including internal system dynamics, stakeholder actions, regulatory oversight at regional, national, and EU levels, and public perception, present both barriers and opportunities in understanding the role of excess heat in DHSs. The underlying *"lock-in"* theory will utilised, and it helps to offer insights into potential barriers that may hinder or facilitate the achievement of predefined goals within DHSs.

3.2 Delimitation

This section will detail the various aspects that are excluded from this study, providing a comprehensive overview of the limitations and the specific areas that are not covered. By outlining these exclusions, the scope and focus of the study will be more clearly defined, ensuring a better understanding of the context and boundaries within which the research operates.

Scale The chosen time period of one year, here from the first of January to the 31st of December 2023, was chosen in order to show the allocation for the different suppliers in practice. It is based on the actual demand and supply from that year. The information is directly provided by the DHS operator Aalborg Forsyning. It is understood to be sufficient to show how the different impacts change and how the changing share of suppliers affects them. By that, the baseline of the last full year since the research was conducted can be used as a point of departure for discussing future changes in scenarios and how the environmental impacts are assessed. The foundation for data could be improved upon by using more continuous years. Yet this was not done due to the recent years before 2023 being somewhat atypical in terms of supply and demand stemming from unusual circumstances coming from a global pandemic and an energy crisis since 2020. Further, was the process of acquiring the necessary data more complicated and took longer than expected due to initial legal uncertainty in the internal processes at the distributor regarding the accessibility of the data. When the issue was resolved, another request would have had to be issued for more information on other years, which would have started the process anew.

Excess heat suppliers The scope of future projections for technological changes in the scenarios for the LCA has been limited to the current and known plans of the DHS operator and the observable practices of the suppliers as of June 2024. This has further been scoped down to Aalborg municipality's biggest DH suppliers. This is also the case with excess heat suppliers. Here, only the biggest suppliers have been included in the study. There is an exclusion of the following excess heat sources; data centres, sewage wastewater treatment and supermarkets. This is done because of the amount time that it would take to accurately model all excess heat suppliers would be too much compared to the relatively low impact it would have. Instead, then is the focus and time spent on the most impactful suppliers of excess heat such as Aalborg Portland, Nordværk and in the future Fjordpark PtX. Furthermore, does this study also not focus on the temperature or the grade of the supplied excess heat, and this aspect is therefore excluded in the analysis and LCA in Section 9. Aalborg Portland and Nordværk have both started to assess and test the possibilities for Carbon Capture Utilisation and Storage (CCUS) Ingeniøren [2023] Nordværk [2023b]. This technology promises to reduce emissions as an end-of-pipe solution and could further open up new use cases for the filtered-out material in PtX as well as providing excess heat from the process itself. For this study, it has been excluded given its early development stage and lack of further knowledge on its potential interaction with the DHS.

Economic and social factors Economic and social factors have been largely excluded from the primary focus of this study. However, they have been partially incorporated with the lock-in theory, serving as contextual information from technological and institutional perspectives. This inclusion helps to understand the current technological landscape and plans for excess heat utilisation. A comprehensive analysis of these factors in relation to the DHS of Aalborg municipality has not been conducted, as it falls outside the scope of this study.

Current legislation This study exclusively examines existing regulations and policies from the EU and Danish law as of June 2024. It does not consider new or forthcoming legislation in development at the time or shortly after the study's completion. Future policy changes or potential regulatory shifts occurring after the study's publication are not included in the analysis or discussion.

Use of theory The lock-in theory and its implications on how it feeds into the analysis are used as a background to frame the study of the current and plans for Aalborgs DHS and its environmental impacts. A full in-depth qualitative analysis like other studies for example Corvellec et al. [2013] or Fontaine and Rocher [2024] of every involved and potentially involved actor heavily utilising the method of interviews (20 and 51 interviews) is not conducted. This is due to the focus of the study being targeted towards the environmental impacts of the DHS. This study should therefore not be seen as a comprehensive study of the lock-in theory in relation to the DHS of Aalborg municipality, since this would require a different focus and a different methodological approach.

Theoretical approach 4

This chapter will introduce and discuss the theoretical approach applied in the analysis conducted in this study. First, lock-in theory will be presented in section 4.1 below, and elaborated on how it is utilised in this study. Lock-in theory is introduced and later applied to the case as it is deemed suitable to better understand the environment DHSs are operating in and further to be able to contextualise the insights from the literature review with the case reality. Subsequently, the structures of carbon lock-in and its implications for the case at hand shall be synthesised in the analysis to be able to discuss the potential scenarios and current developments/scenarios for the future on the background of the criteria for a lock-in situation.

4.1 Lock-in theory

The lock-in theory stems from the studies of energies and policy and was first phrased in that way by G. C. Unruh in 2000. He described the phenomenon of how existing technology, institutions and social forces create a so-called "*lock-in*" situation through their systemic interaction Unruh [2000]. In that, the technologies that are part of this complex system experience an increasingly advantageous development compared to technologies outside of the system due to a *"path-dependent, co-evolutionary process involving positive feedback among technological infrastructures and the organisations and institutions that create, diffuse and employ them"* [Unruh, 2000]. Problems arise when alternative technologies that are not part of this dynamic, that the system has locked-in, perform better on specific aspects. Due to the lock-in dynamic better technologies are disadvantaged in their implementation, this is then called "*lock-out*".

Unruh [2000] established this specific theory the first time by connecting technological *and* institutional lock-in. It needs to be emphasised that lock-in situations can be observed in many disciplines and have been before Unruh, especially the ones concerned about transitioning to more sustainable practices. A recent review by Goldstein et al. [2023] covers the multiple ways in which different disciplines contextualise and use lock-in theory. Here the focus shall lie on energies, its problems and policies related to carbon lock-ins and other, as the literature review indicated, usually less investigated issues in relation to emissions and environmental impacts. Carbon lock-in stems from a specific type of path dependency. This often occurs in complex systems as they are *"particularly prone to entrenchment given the large capital costs, long infrastructure lifetimes, and interrelationships between the socioeconomic and technical systems involved."* Seto et al. [2016]. In their review Seto et al. [2016] conceptualise three main types that concern carbon lock-ins and their path dependency in order to point out the intricacies of how different aspects of the same system rely on each other and can prolong/entrench/strengthen lock-ins in an energies related system.

1. Lock-in associated with the technologies and infrastructure that indirectly or directly emit CO_2 and shape the energy supply.
2. Lock-in is associated with governance, institutions, and decision-making that affect energy-related production and consumption, thereby shaping energy supply and demand.
3. Lock-in related to behaviours, habits, and norms associated with the demand for energy-related goods and services.

The relevance of this study can be established through the concern of decarbonisation alone but can be further reinforced by concerns in regard to other possible environmentally detrimental impacts of current practices. The expected outcome can be information on current practice by adding to the known information about resource usage and thus lead to a wider basis of knowledge and decision-making foundation to operate from to avoid disadvantageous path dependencies in the future. As Seto et al. [2016] points out, lock-ins themselves are not necessarily negative. Only the specific practice that appears to be locked in can be. It is so that lock-ins can also favour a practice that furthers a cause or practice which is deemed positive.

Goldstein et al. [2023] connects *"path dependency"* to lock-in theory. In energy-related use, it is most often the problems of carbon lock-ins that are being addressed. Unruh [2000] established the theory in order to understand the barriers that prevent the phase-out of carbon fuel sources from the energy sector due to pre-established practices and preferences whether they be economic or societal. Through this, a so-called *"Techno-Institutional Complex"* (TIC) arises. This is the description of a lock-in system with all its entrenchment mechanisms working in interrelation forming an *"inertia"* that strengthens the TIC and its included technology against technological entrants Unruh [2000].

Interconnected technologies and industries have evolved into what they are nowadays. The systems (and TIC) we are confronted with today are the product of their development in the past. The TIC that provides *"carbon lock-in"* has been established and evolved since the start of industrialisation. Shifting goals over time can lead to systems that are optimised for former goals and are sub-optimal for new or more recent demands to a system such as decarbonisation. van Staveren and van Tatenhove [2016] differentiate that "*path dependency emphasises future development of a system, whereas technological lock-in emphasises a certain system state*" at a present moment in time. The problem lies herein that such complex and interconnected systems such as DHSs or the energy supply of cities in general are systems established over time and for some, the hardware has been part of local infrastructures for decades. This makes adaptations harder due to complexity. Decisions nowadays need to be made from within this existing system as path dependency has led to this situation and influences the set of most reasonable solutions. It could be argued that the current possible decisions are limited by the decisions made in the past. This makes it easier to continue the current *"path"* as the TIC supports the current practice. As the TIC is embedded in socio-economic, technological and political interaction supporting it Goldstein et al. [2023], it can also be altered or dissolved by these elements if such decisions are taken by the respective institutions.

Unruh [2000] described the process of establishing a TIC can be broken down into steps. These steps can not only be used to understand and analyse current TICs but also how new ones can be formed or prevented. These steps are:

1. An initial event setting off the development (has an element of randomness).
2. Positive feedback loops form around elements of a new system.
3. A network effect attracts more users and gets stronger the more users there are as the value of a new technology rises with its capacity to be interconnected with other technologies and users.
4. A *"lock-in"* of the most competitive practices occurs.
5. The technologies and practices that have now been amplified and supported by the positive feedback loops leading to a system that disadvantages every other technology that is not *"locked-in"* due to high entrance barriers (especially in the built infrastructure sector).
6. The *"lock-in"* works as an attractor leading to the dominant technology to also become the easiest possible solution supported by the elements that make up the TIC. Other competitors then have even less chance to break into a system or market.
7. The system has now established inertia meaning a resistance or negative reaction to any obstructing outside change attempts and becomes thus more self-perpetuating and inhibits better solutions for new goals.

It needs to be emphasised that the process is highly sensitive to the initial conditions which can often only be observed and understood afterwards.

Unruh [2000] explains that the lock-in can be broken. For that either highly efficient technology becomes available or organisations work closely together in order to establish change through widespread cooperation towards a common goal. Standardisation can be a helping aspect in this and lead to strong new lock-ins. He also followed up on the act of dissolving and avoiding lock-ins in a dedicated article on it in 2002 Unruh [2002]. The socio-political *"domain"* here influences the development of technologies by the choices that are preferred and fostered within them.

4.2 Lock-in in relation to district heating systems

DHSs are inherently interconnected with their surrounding technologies and society which is shaping the policy enabling or hindering its further development. Historically DHSs have been running on fossil-based fuel sources, yet in the recent past, there have been an increasing amount of new system approaches to incorporate different types of fuel and excess heat from other processes. With the current EU legislation on energy efficiency and reduction of fossil-based fuel being usedEU [2023], it could be argued that the preexisting *"inertia"* of the carbon-based TIC is not as strong as it used to be, thus being already less *"locked-in"*. Further considerations in the case of Aalborgs DHS are covered in the discussion, 11.5, including different scenarios and the relevant aspects of the existing TIC as well as the recent relevant developments. An example from the Swedish city of Göteborg (Gothenburg) is presented here.

To make the mechanisms and different involved entities in a carbon lock-in more understandable an example from the field of DHSs can be used. Corvellec et al. [2013]

stated an example of a lock-in related to waste incineration heat used in the DHS of Gothenburg. This can serve as an explanation of how an established TIC affects the area it is occurring in and who plays which role in the dynamic that represents the inertia of the TIC. The city of Gothenburg and its DHS can be deemed similar in several aspects to the city of Aalborg and its DHS. In their study, they used Unruh's theory in order to explain why the DHS of the case evolved the way it did, what dynamics and structures came to be through it and what new problems it entailed.

Subsequently, there are some new options mentioned that can now be pursued or not due to entrance barriers or other lock-in-related dynamics created by the inertia of the existing TIC. Their description of the situation was based on the Swedish waste governance development and how it favoured the incineration of waste as a better solution than landfills. A similar legislation is supporting DHS-related waste incineration in Denmark [Miljøstyrelsen, 2004]. The cogeneration of heat in the waste incineration process has proven to be a good use case for heating in DHSs and has a stable, fairly cheap resource. This initial development is almost fifty years in the past by now. Continuous reinvestment into the infrastructure and expansion of the incineration capacities has increased the distributed heat and at the time of the study was substituting 175.000 m^3 of oil or 160 million m^3 of natural gas [Corvellec et al., 2013]. Inhibitions and barriers to new development of innovative technologies arose through the path dependency that has been created by the focus on waste incineration. Corvellec et al. [2013] state that this path dependency can manifest by the already committed resources and built-up technical prowess of the involved operators and contractors. The high investment cost for new hardware infrastructures and the long payback times of the existing ones made new technologies seem less viable in this case biogas extraction from waste. This coincides with Unruh [2000] point regarding reoccurring re-investments into the existing locked-in system in which innovative technologies need to be introduced by new entrants to the sector rather than the dominant actors. In a regional monopoly like the DHS operator which was operating on the by then most economically feasible solution. Further, recycling and waste prevention measures proposed by one of the parties in the municipality were deemed less important an option even though they presented a solution with less environmentally detrimental impacts.

Using the steps presented earlier, this is how the lock-in case of Gothenburg by Corvellec et al. [2013] can be broken down into phases:

1. The initial event for Gothenburg's waste incineration system was the waste disposal crisis and the oil price shocks of the 1970s. These events created a need to find alternative methods for waste disposal and heat production.
2. The establishment of the Sävenäs incineration plant, which could provide both waste management and DH, created positive feedback loops. The plant's ability to convert waste into energy supported the city's energy needs and reduced reliance on landfills, thus catering towards efficiency and sustainability.
3. As the incineration technology proved successful, the Sävenäs plant became a critical component of the Gothenburgs heat infrastructure, connecting with the DHS and other municipal services, thereby increasing its value and entrenching its position within the urban infrastructure.

4. Over time, the practice of waste incineration became locked-in as the dominant method for the city's waste management. The extensive investment in the infrastructure, along with its integration into the city's heat supply, made it difficult to adopt alternative practices. The continuous improvements and expansions of the Sävenäs plant amplified its dominance. The plant's high efficiency and the significant heat output it provided further cemented its role. This reinforcement created high entry barriers for other technologies, making it challenging for alternatives like waste-to-biogas or enhanced recycling efforts to gain traction.
5. The entrenched system of waste incineration became the path of least resistance, supported by the established technological, economic, and political frameworks. The convenience and existing support systems for incineration meant that even as calls for more sustainable practices grew, the momentum to maintain the status quo was strong.
6. The system's inertia became evident as stakeholders, including local politicians and the public, viewed incineration as an effective and proven solution. This resistance to change was argued for by the substantial investments already made and the risks associated with shifting to unproven alternatives. When the waste incineration plant was expanded and faced shortages in local waste, imports from Denmark and Norway had to be made to fulfil the capacity required to operate the DHS. Some interviewed stated that the cooperation between the municipality and the board of the publicly owned company could have been better in order to make other technological options like biogas production more feasible to invest in for the DHS operator.

The study closes with proposals for an *"unlocking impetus"*. In the observed case, waste minimisation and technological solutions for waste management were already argued for by political parties. The time component can play a significant role here as the prospected and already fulfilled lifetime of the infrastructure can determine if the danger of *"stranded assets"* hinders change or conversely serves as a great opportunity for changes when need for maintenance repairs or investments for prolonging the lifetime are needed anyways. The unlocking or adaptation of the situation needs *"a sequence of events acting as a catalyst for concerns and initiatives"* Corvellec et al. [2013]. Here it is also mentioned that the involved actors in future planning need to show a willingness for change and be aware of the aspects that either support or inhibit the unlocking process.

Aligned with the described dynamics in the foregoing section Goldstein et al. [2023] observed similar dynamics. There can be various sources for the lock-in phenomenon depending on the situation. For the study at hand the existing infrastructure can already have established *"hard"* and *"financial"* lock-ins as for both there have already been infrastructures established potentially locking out newly developed solutions or sunken costs making changes harder. The existing consumption and production patterns can lead to preferred practices of companies. Also, certain values, preferences, and ways of viewing the environment can favour specific, established practices. Goldstein calls them "environmental values" [Goldstein et al., 2023].

Relating to possible changes and the establishment of a beneficial new TIC Yona et al. [2019] point out that path-dependent mechanisms, also from policy institutions, can lock-in renewable energy by guaranteeing long-term incentives or subsidies, making use of the positive feedback loops and occurring path dependencies that lie in this practice. This in turn can then also lead to political new support. Through that Yona et al. [2019] show that *"lock-in"* mechanisms and path dependency do not always or inherently have to be sub-optimal or bad but support the goals that stem from a more comprehensive understanding of the surrounding system and environment. They can be used to strengthen the desirable outcomes, systems, or technologies (here also fuel types). This is and will be salient in assessing transitions away from fossil fuels and towards renewable energy at multiple scales.

Applicability in this study lies in the question if, and if so to what extent, the current situation of the case resembles a *"lock-in"* as described in the literature. By using the theory it can be categorised if and what is contributing to a continuous carbon-reliant path by relying on fossil-based carbon-intensive fuel types in the long-term development and how the assumption of excess heat to be environmentally neutral (CO_2-free) affects the way how these impacts are reported and taken responsibility for. Further, it stands to analyse if the current situation is prolonging the use of carbon-intensive fuels and processes thus inhibiting the implementation of substitute technologies. Counterarguments that efficiency gains alone, supported by path-dependent processes, institutions and policies, could be sufficient on its own need to be weighed in. Additionally, the definition of excess heat and the allocation of CO_2 burdens can be viewed through the perspective of a current TIC that potentially prolongs its lock-in. This issue will be investigated in Section 8.

For combining the case area and carbon lock-in theory the historically path-dependent situation of the present needs to be addressed. The combined efforts and actions of the local companies and the municipality as well as national members of the TIC around the usage of carbon-based energy sources can be identified and have differing goals depending on their agendas and responsibilities. This will be further investigated in Section 8.1.

5 Research design

To address the research question and its sub-questions, which are presented in section 3, a research design has been developed to guide the overall structure of this study. This design aims to establish a systematic framework for answering the research question. This section outlines the methodological foundations used in this study and demonstrates how they are utilised to address the research questions. Figure 5.1 below illustrates the research design.

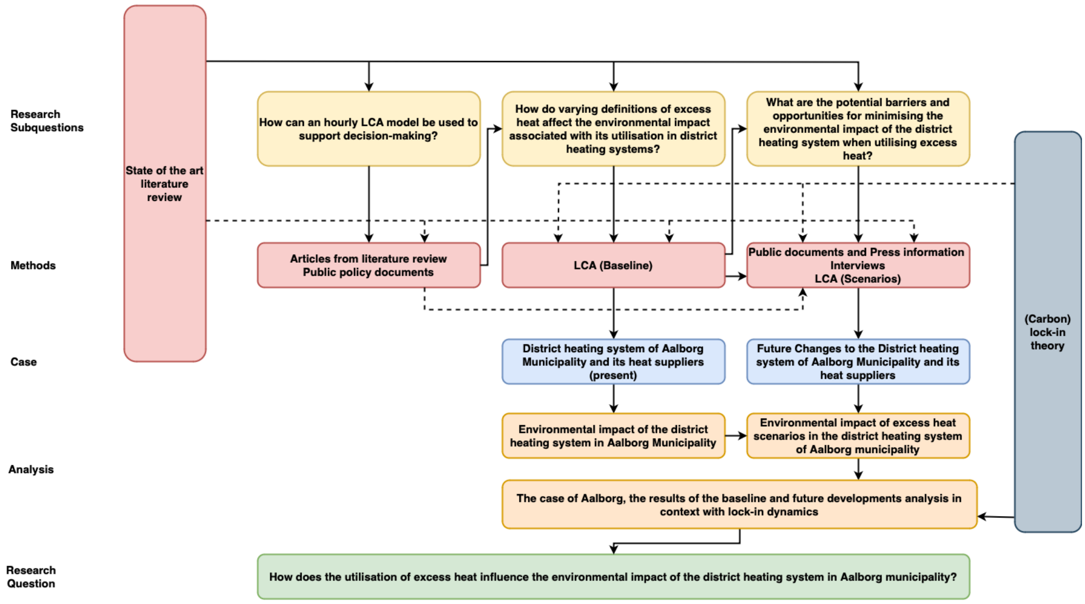

Figure 5.1. Research design (dashed lines for easier overview)

The figure shows the structure of the study which is shaped by the three sub-questions presented in section 3. The sub-questions each address different aspects of the study, with the first sub-question focusing on how the environmental impact of the DHS changes throughout time, aiming to gain insight into how the environmental impact fluctuates based on time-dependent demand and the suppliers being used to meet the demand. To answer this question, an LCA is performed on the current DHS in Aalborg municipality. The LCAs are performed at an hourly level, resulting in a large amount of LCA results that will show how the environmental impact of the DHS fluctuates throughout a specified period. The results are analysed to explore how not only the often considered CO_2-emissions are changing but how other impacts are affected by the changing share of heat supply to the DHS. The second sub-question focuses on the issue of defining excess heat, investigating the effect that allocating environmental impacts to excess heat has on LCA results. This will give a better understanding of the environmental impact of excess heat and the importance of a common approach and understanding of the term. The third and final sub-question looks at the barriers and opportunities for utilising excess heat in Aalborg municipality. While the LCA can give insight into the environmental impact of the DHS and the use of excess heat, this sub-question aims to investigate the practical factors that are limiting or enabling the increased use of excess heat. This sub-question will furthermore help shape the scenarios that are investigated in the LCA and will be answered through an interview and literature study. This entails future changes to the system. The current situation as well as the future changes are analysed on the background of how the present came to be and why the plans were chosen by the involved decision makers. The theory of (carbon) lock-in is used to look at the case and its development through the lens of if and how the decisions currently came to be and how they might be affected by lock-in dynamics. The newly acquired perspective on the environmental impacts is also contextualised with a potential lock-in dynamic and that might show room for improvement or present other problems that are currently not addressed in the decision-making for the goals which the DHS is developed towards.

To help contextualise the study the case of Aalborg municipality has been chosen. The chosen case is described in depth in section 7. The decision to use a case for this study is based on the desire to use real data, as well as provide results that can be used in a real-world context as well as to understand how a system like this is shaped by the relevant decision-makers.

Several methods are used in the study, LCA, interview and literature review, as well as a background of regulatory documents which is relevant to the way how DHSs in Denmark are supposed to operate. An in-depth description of how these methods are used in this study can be found in section 6. By using these methods in the context of the three sub-questions and the case of Aalborg municipality, it is possible to answer the main research question stated in section 3.

Methodology 6

This section will elaborate on the various methods and concepts that have been used in this study. Firstly, the state-of-the-art literature review will be presented, followed by a section that explains the interview method. LCA as a method will be presented, and an outline of how these different methods will be integrated and used in the study.

6.1 State of the art literature review

In this study, it was chosen to conduct a state-of-the-art literature review. This is done to identify existing knowledge within the research field of this study. Such a literature review can be conducted by using different methods, but in this study, a systematic review approach is utilised [Snyder, 2019]. This approach was selected to systematically identify and arrange all current relevant literature within the specified research field, thereby mitigating potential biases. The literature review serves as the foundation when acquiring new knowledge to use within the study. It also offers the opportunity to provide an overview of how different areas where the research, that has already been conducted, differentiate from each other [Snyder, 2019]. Moreover, it facilitates the identification of areas where research is scarce or even nonexistent, thereby pinpointing so-called *"knowledge gaps"* within the research field of the study [Snyder, 2019]. These knowledge gaps will help to steer the study towards areas of the research field where further research is needed, and where this study could fill out the identified knowledge gaps. Besides guiding the study's path and finding areas of key interest in the research field, the literature review also contributes to evaluating the study's validity [Snyder, 2019].

In this study, the primary methodology adopted for conducting the literature review draws inspiration from the four phases outlined in [Snyder, 2019].

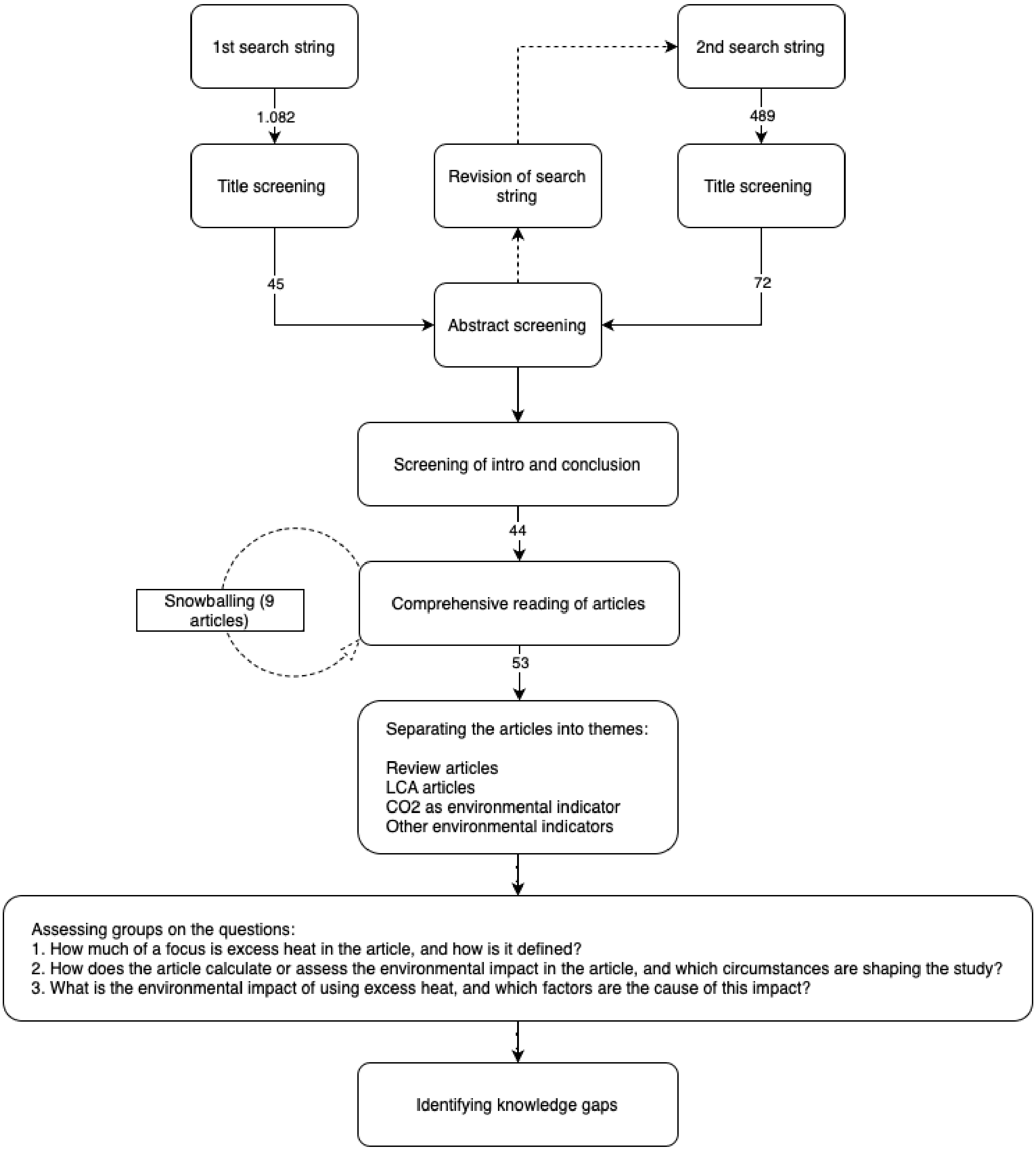

Figure 6.1. Literature review process

In figure 6.1, an overview of the literature review process can be seen, starting from the initial search and ending with the analysis of the identified articles. The elements of the process are explained in depth in the following section.

Phase 1: Designing the literature review

During the first phase of the literature review, the structure and design of the review is settled upon. To design the literature review in the best possible way, the purpose and objective of the literature review first need to be stated. For this study, as presented in Chapter 1, the objective of this literature review is to gain insight into the current research on the environmental impacts of using excess heat in DH.

As part of the design phase, a search strategy was formulated to ensure the right utilisation of the most relevant terms and databases. Preliminary search constraints were implemented to maintain result relevance. To refine the review, it was decided to limit the scope to environmental impacts, excess heat and DH. Additionally, the review only included literature published between 2014 and 2024, aligning with the objective of identifying current and the newest literature regarding the research field. However, to ensure that no key articles were missed due to this limitation, articles older than 2014 were considered when using the snowball method on the identified articles. No geographical limitation was added since all research about the environmental impacts of including excess heat in DH would be relevant no matter the location. Finally, a language restriction to English was chosen.

During the preliminary search phase, various databases and search terms were evaluated and tried, and those yielding the highest number of results were identified. Subsequently, databases with the most extensive results were selected, namely: Scopus, Web of Science, ProQuest, ScienceDirect, EBSCOhost and lastly Engineering Village. The literature search ended up consisting of two iterations of similar versions of a search string.

The first search string consisted of two parts:

1. A term describing excess heat. For this literature search the terms *excess heat*, *waste heat* and *surplus heat* were used.
2. A term describing *environmental impact*. The terms *environmental impact*, *environmental effect**, *LCA*, *life cycle assessment*, *environmental assessment** and *environmental footprint*.

However, based on the initial screening of the articles found using this search string, another search string was created. This was deemed necessary as the initial search did not cover articles focusing on excess heat in DHSs with a focus on environmental impacts sufficiently. To ensure that relevant articles were not left out using the first search string additional terms were added. The term *"district heat"* was added to specify the context in which excess heat would be studied, while emission was added to catch a broader scope of articles that might not directly mention environmental impact or similar terms. This second search string was found to be sufficient, as these terms were assumed to cover all relevant articles on the topic.

The second search string used in the databases can be split into three parts:

1. Same as for the first search string
2. Same as for the first search string, with the addition of the term *emission**
3. A term describing district heating. Here the term *district heat** was used.

The terms in the specific parts of the search strings were separated by the boolean operator OR. This had the purpose of specifying that only one of the terms in each part of the search strings had to appear in the article. E.g. excess heat OR waste heat OR surplus heat. The different parts of the search strings were combined with the boolean operator AND, meaning that at least one term in each of the parts had to appear in the article. Furthermore, quotation marks were used to make sure that only articles with exact matches with the terms in the search strings would appear in the search. In connection to this, an asterisk was used with terms such as district heat, to specify that different forms of the term, such as district heat*ing*, were valid matches. The search strings had to be tailored for each database, as the databases had different syntaxes for their search functions. However, all searches followed the structure and elements described above. The search strings were applied to the title, abstract and keywords of the articles.

This search is limited to publications between 2014 and 2024, and restricted to English-language academic articles. It was discovered when going through the titles of the articles from the initial search, that a lot of the results extended beyond the intended scope of the literature review. The articles that fell outside the scope focused on a single technology or a technical aspect of a technology, which is not the focus of this study. Therefore, these articles were discarded during Phase 2 of the literature review.

Subsequently, a manual process was undertaken to further eliminate articles falling outside the scope of this literature review, which is presented in Phase 2 in the section below.

Phase 2: Conducting the literature review

Phase 2 is the stage where the review is actively conducted, and the definitive literature is chosen. The initial search across the selected databases using the first search string yielded a total of 1.082 articles. The search using the second string yielded 489, not including duplicates that were already found in the first search, for a total of 1.571 articles. The distribution of these articles among the six chosen databases is detailed in Table 6.1 below.

Name of database	**Hits**
Scopus	600
Web of Science	187
ProQuest	288
ScienceDirect	191
EBSCOhost	58
Engineering Village	247
Total	**1.571**

Table 6.1. Results from each of the six chosen databases using the final search string.

The results from each database were exported into RefWorks, which is a reference management software. This software was used to remove duplicates from the search results.

Subsequently, it was determined that splitting the selection process into distinct stages would help to ensure the validity of the selection phase. The initial stage involved manually reviewing the results of the search to assess if the titles fell within the scope of the review and adhered to the aforementioned limitations that are mentioned in 6.1. The outcome of this stage is illustrated in Table 6.2 below.

Name of database	Hits
Scopus	48
Web of Science	5
ProQuest	19
ScienceDirect	9
EBSCOhost	6
Engineering Village	30
Total	**117**

Table 6.2. Results from each of the six chosen databases after manually going through the titles.

Upon examining the results, from Table 6.2, it can be deduced that manually going through all of the titles of the articles proved to be quite an effective process. Merely by looking at the titles of the articles, the number of hits decreased from 1.571 to 117. Here, sources were primarily rejected due to being too technical, focusing on a very specific technology, or not focusing on any of the terms specified in phase 1.

In the third stage, the abstracts of the sources were manually reviewed to determine if they fell within the scope of the literature review in this study. The outcome of this process is depicted in Table 6.3 below.

Name of database	Hits
Scopus	26
Web of Science	2
ProQuest	3
ScienceDirect	2
EBSCOhost	1
Engineering Village	10
Total	**44**

Table 6.3. Results from each of the six chosen databases after reviewing the abstracts.

This process also proved effective, reducing the total number of sources from 117 to 44. Reading through the abstracts, it could be seen that a large portion of the 117 articles did not have the environmental impact of excess heat and district heating as one of the key aspects of the study, and were therefore deemed to be outside the scope of this literature review.

During the fourth stage of phase two, the identified sources underwent thorough examination to definitively assess their relevance and ensure they fully met the inclusion criteria. This process followed a predetermined systematic approach to ensure that the identified articles so far all got the same treatment. Initially, the abstract of each source was reviewed, followed by the conclusion/discussion, then the methods and theory, and finally the results/conclusion. The outcome of this selection process is presented in Table 6.4 below.

Name of database	**Hits**
Scopus	20
Web of Science	1
ProQuest	3
ScienceDirect	2
EBSCOhost	1
Engineering Village	8
Total	**35**

Table 6.4. Results from each of the six chosen databases after a thorough and systematic reading of all sections.

To ensure thoroughness and reduce the possibility of oversights in the source selection process, the references of the chosen literature were reviewed. This led to the discovery of additional articles that were relevant and within the scope of this literature review. In total 4 articles were identified from this process, bringing the final number of relevant articles to 39. These articles will be analysed further during phase 3 in Section 6.1 below.

Phase 3: Analysing the results

Following the final selection of sources in phase 2, an overview of the information contained within these articles is conducted as part of phase 3. This is undertaken to extract the relevant information from the literature. This process involves categorising the chosen articles into different themes that align with the predetermined purpose of the literature review that is stated in phase 1. In practicality, the categorisation is based on what the different articles have in common based on their research and findings. The identified articles from phase 2 are grouped into four main themes which are:

- Review articles
- Articles looking at the environmental impact from an LCA aspect
- Articles looking at the environmental impact, only focusing on CO_2-emissions.
- Other. Articles that do not fit in the two previous groups. E.g. articles that look at other environmental impacts besides CO_2-emissions, but do not perform an LCA.

. The groups and what can be deduced from them are presented in chapter 2.

Phase 4: The structuring and writing of the literature review

In the fourth and concluding phase of the literature review, the actual review is organised and composed. This organisation is derived from the themes and categories identified in phase 3, resulting in the review being structured into sections that focus on each of the four themes. The way each theme has been analysed has been to some extent tailored to that specific theme, but some aspects are looked at across all of the four themes, like the definitions of excess heat, the circumstances for the study and the findings. They differ in that the LCA category will look at LCA-related aspects such as the system boundaries and the impact categories that are used, and for example with the articles looking at CO_2-emissions the calculations for these studies will be looked at. The fourth phase concludes with an overview of the identified knowledge gaps drawn from the entire review and these are then condensed into the key conclusions in Section 2.5 that will serve as the focal point and be utilised as the foundational knowledge throughout the study.

6.2 Life Cycle Assessment

The LCA method is used for assessing the environmental impact of using excess heat in a DHS.

LCA is the primary method that is used in this study. LCA is a systematic and comprehensive method that is used to evaluate the environmental impact of a product or service/process such as the given case of a DHS. Here the life cycle of the declared product, material or service/process is considered in the LCA. ISO standards provide the general assessment frameworks for the LCA but the way it is conducted depends on the subject of analysis. In this study, a process is being analysed that is different to the LCA of a product as it is a continuous process which changes over time. The LCA is based on the ISO 14040 and 14044 standards.

ISO 14040 states the requirements and guidelines on how to perform an LCA. Further details and requirements for practitioners for conducting an LCA are presented in ISO 14044. It further states the varying purposes for conducting such assessments [Organisation, 2006b].

- Help in the identification of opportunities to improve the environmental impact of a given product at different stages of its life cycle.
- Help in informing decision-makers in both industries and governmental institutions as well as non-governmental organisations.
- Help with the selection of the most relevant indicators regarding environmental performance and methods of measuring those.
- And help in relation to marketing such as the making of an Environmental Product Declaration for a given material/product.

Regardless of the purpose, it is to be conducted in four Phases. In the first phase, the goal and scope of the LCA need to be decided. In phase two the life cycle inventory (LCI) is to be set up. The third phase is the life cycle impact assessment (LCIA) and the final phase is regarding the interpretation and discussion of the LCA. These phases are presented in more detail below.

These four phases are described in Chapter 9.

Consequential life cycle assessment

The LCA that will be conducted in this study will be performed as a CLCA study. The reasoning for conducting a CLCA study is because of its ability to assess the potential downstream impacts of different decisions or actions within a life cycle [Ekvall, 2020]. Unlike ALCA, which focuses on the immediate impacts of a product or process, CLCA considers the broader systemic effects, including indirect and long-term consequences [ibid.]. This approach can provide a more comprehensive understanding of the environmental implications of various choices, allowing decision-makers or actors to account for potential trade-offs and unintended effects and make more informed choices [Ekvall, 2020].

CLCA is suited for evaluating the environmental impacts of utilising excess heat in Aalborg's DHS due to its comprehensive and dynamic nature. Unlike ALCA, which focuses on attributing environmental impacts to specific products or processes, CLCA examines the broader systemic changes and market-mediated effects that result from decisions.

Furthermore, CLCA provides insights into how integrating excess heat influences the overall energy system, including shifts in electricity production and market dynamics. This approach is important for understanding the complex interactions within Aalborg's energy landscape and aligning with the study's goal to assess the environmental impacts of different scenarios regarding excess heat utilisation.

6.2.1 Hourly life cycle assessment

As identified in the literature review in section 2, the temporal aspect of excess heat in DHSs is often overlooked in LCAs on the subject. To include this aspect in this study, data from the Ecoinvent database is used to calculate factors for the environmental impact of producing and supplying 1 kWh of heat in the DHS of Aalborg municipality. These factors are then used in conjunction with data for the specific production of the heat in the municipality on an hourly basis. Furthermore, the external impacts of heat production are taken into account. In the data collection process, hourly heat production data was gathered for the year 2023 from all the major heat suppliers in Aalborg municipality: Nordjyllandsværket, Nordværk and Aalborg Portland.

The hourly data was obtained from Aalborg Forsyning, the utility company responsible for the DHS in Aalborg municipality. For other suppliers, meaning the electric and natural gas boilers, no hourly or daily data was collected. Instead, their heat supply was allocated to the hours when the total heat supply was delivering less than 50% of the heat demand.

The hourly data from Nordjyllandsværket, Nordværk, and Aalborg Portland were integrated into the analysis to provide a detailed temporal resolution of heat production and its environmental impacts, and the results from this are presented in 10. Including an hourly LCA model is particularly relevant because the share of heat supplied by each source varies significantly over a year, month, or even day.

"*Temporal aspects*" in the context of conducting an LCA on excess heat utilisation in DHS refers in this study to the consideration of time-related factors that influence the availability and demand for excess heat throughout different seasons, times of day, and years. This includes assessing fluctuations in heat production, distribution, and consumption over time, as well as how these variations affect the environmental impacts associated with utilising excess heat in DHS.

The environmental impact factors for producing and supplying 1 kWh of heat from each supplier in Aalborg municipality were modelled in SimaPro by using generic datasets from the Ecoinvent database. The modelling of environmental impact factors is presented in section 9.3 and the results are presented in section 9.5. These factors included various environmental impact categories relevant to DHSs. By applying these factors to the hourly heat production data, the temporal variability of environmental impacts could be assessed.

6.2.2 Allocation of environmental impacts

In this study, the environmental impacts associated with district heating are allocated based on the contributions of each heat supplier. The key heat suppliers considered are the CHP, Nordjyllandsværket, Nordværk, Aalborg Portland, a natural gas boiler, and an electric boiler. The allocation factors are determined by the share of heat supplied by each source. These shares are based on data from the hourly heat supply of 2023, which is explained in Section 6.2.1.

The environmental impact is calculated by taking the hourly heat supply from each supplier and multiplying it with the impact category factor for the individual heat supplier. The impact category factors can be seen in Table 9.5.

Allocation of environmental impacts for excess heat

This section will present the method that is used to allocate environmental impacts for the excess heat that is used in the DHS of Aalborg municipality. The method described in this section will therefore be applied exclusively to the heat generated by Nordværk, Aalborg Portland, and Fjordpark PtX, as these are the only suppliers of excess heat that are included in this study.

As presented in 2 different terms are used for defining excess heat, such as *true* and *false* and *unavoidable* and *avoidable* excess heat. These terms are not used to define excess heat in this study. The reason that these terms are not used, is that they require a thorough insight into the supplier of the excess heat and an in-depth understanding of the production facilities that generate the excess heat. Instead, excess heat is considered to have an environmental impact proportional to the resources or fuel required to generate it.

In this study, the allocation of environmental impacts for excess heat is based on the proportion of excess heat relative to the total heat generated by each heat supplier. This method ensures that environmental impacts are appropriately attributed to the excess heat used in the system.

To determine the allocation factors for each excess heat supplier, the calculation must consider the proportion of excess heat relative to the total energy generated by each supplier. For instance, if the excess heat constitutes 25% of the total heat or energy generated by a supplier, then 25% of the environmental impacts from that supplier will be attributed to the excess heat.

This method is chosen as it does not require in-depth knowledge of the excess heat-producing processes, while still ensuring a fair evaluation of the environmental impact of producing the excess heat. It is deemed fair as it is not the total environmental impact of the process that is allocated to the excess heat, but only a corresponding amount. Using this approach, the bigger the share of the total energy production that is excess heat, the bigger the share of the environmental impact allocated to the excess heat will be. As a result, the environmental impact of the excess heat will technically be larger the bigger the share of the total energy production used for district heating. This might seem illogical, however, this aspect is outweighed by the use of the consequential modelling approach. When modelling the excess heat consequentially, the amount of excess heat is modelled as substituting the primary heat production, thus avoiding the environmental impacts of the corresponding primary heat production. The avoided production of primary heat is equal to the amount of excess heat supplied to the DHS, and therefore the bigger the share of the total energy is utilised as excess heat, the primary heat production is avoided.

The determined allocation factors are used by assigning a portion of the environmental impacts from each heat supplier to the excess heat utilised in the DHS. This ensures that the impacts are proportionally allocated based on the actual contribution of excess heat.

7 Case of Aalborg municipality

To investigate the environmental impact of utilising excess heat in a DHS on a detailed temporal level, the Danish municipality of Aalborg has been chosen as a case. The choice of case is based on Aalborg municipality having an extensive DHS with a large potential for excess heat [Sorknæs et al., 2020]. These factors along with there being a large amount of research and data on the excess heat potential and DHS of Aalborg municipality make it a fitting case for this study.

7.1 The district heating system of Aalborg municipality

The municipality of Aalborg inhabits, as of 2021, 219.487 citizens in an area of 1.137 km^2 [Energistyrelsen, 2021a]. The municipal borders of Aalborg municipality can be seen in Figure 7.1. Based on numbers from Energistyrelsen [2021a], 88% of the municipality is covered by DH, with work actively being done to increase this number [Aalborg Kommune, 2022]. DH contributes 83% of the CO_2-emissions from heating production in the municipality [Energistyrelsen, 2021a].

The DH in Aalborg municipality consists of a central power and heat co-generation area, with ten decentralised DH areas [Aalborg Kommune, 2022]. The DHS is primarily based on the incineration of coal and waste, as well as excess heat [Aalborg Kommune, 2022]. Aalborg municipality has a goal of only using fossil-free fuels in the DHS by 2030, by, among other actions, utilising more of the excess heat from industry and retail [Aalborg Kommune, 2022].

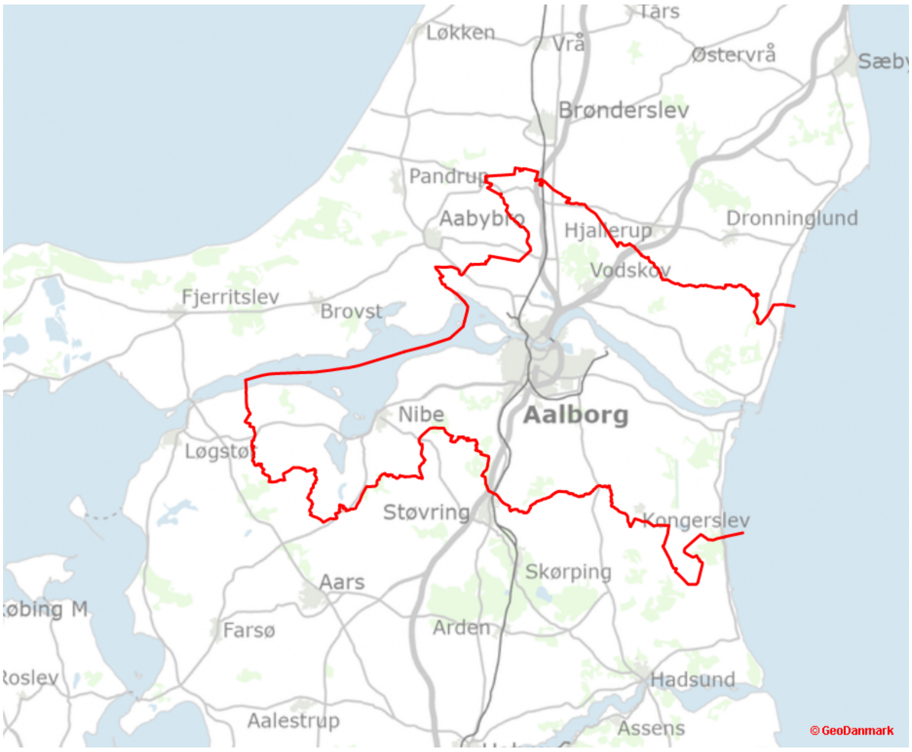

Figure 7.1. The borders of Aalborg Aalborg Municipalty [2024]

The Figure above, 7.1, showcases the case area, the municipality of Aalborg, which is within the red borders.

The different fuel types that are used to produce the DH in the municipality of Aalborg range widely between less than 1% to 38% as shown in Figure 7.2 Aalborg Forsyning [2023a].

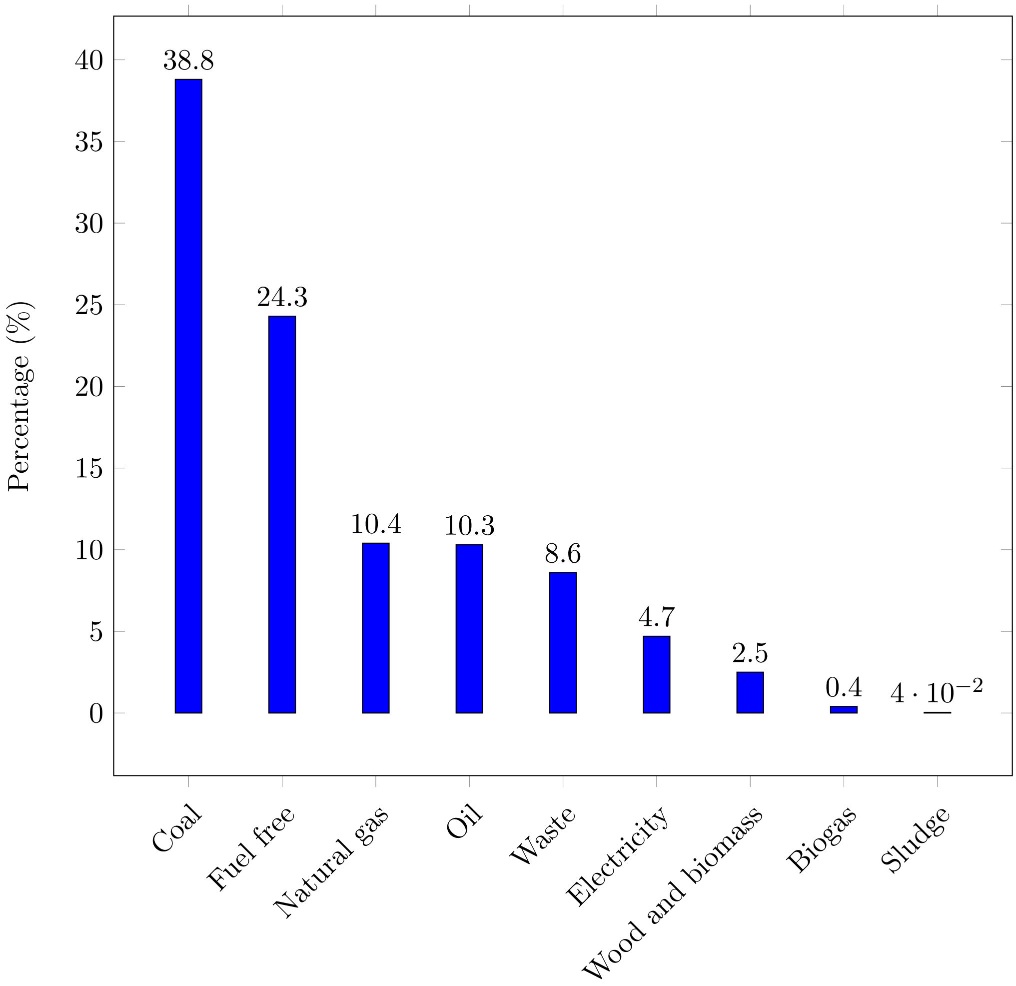

Figure 7.2. Share of DH based on energy sources

As stated earlier in this Chapter, then it can be seen in Table 7.2 that coal, with 38,8%, is the primary fuel type that is used to produce DH in the municipality of Aalborg. *Fuel free*, which is defined as excess heat by Aalborg Forsyning, is the second most utilised fuel type, with 24,3% usage Appendix A. In the least used category of fuels are biogas and sludge.

The share of renewable energy that is used to produce DH in Aalborg municipality is at 36,1% [Aalborg Forsyning, 2023a]. The environmental impact per kWh of delivered DH can be seen in Table 7.1 below based on data from Aalborg Forsyning [2023a].

Greenhouse Gas	**Emissions per kWh**
CO_2 (Carbon Dioxide)	121.12 g
CH_4 (Methane)	3.13 mg
N_2O (Nitrous Oxide)	1.49 mg
Total Greenhouse Gases (CO_2 equivalents)	121.61 g
Pollutants	**Emissions per kWh**
SO_2 (Sulfur Dioxide)	10.52 mg
NO_x (Nitrogen Oxides)	72.22 mg
CO (Carbon Monoxide)	33.86 mg
NMVOC (Non-methane Volatile Organic Compounds)	2.30 mg
Particles (TSP)	4.97 mg

Table 7.1. Environmental impact of energy sources. Based on Aalborg Forsyning [2023a]

As it can be seen in Table 7.1 the total GHG emissions from one kWh of delivered heat 121,61 gram of CO_2-equivalents [Aalborg Forsyning, 2023a].

7.2 District heating suppliers in the municipality of Aalborg

This Section will present the different suppliers that produce heat for the DHS of Aalborg municipality. There are three main suppliers of DH in the municipality of Aalborg and some smaller suppliers, and these are; Nordjyllandsværket, Nordværk, Aalborg Portland, and then also the group of smaller suppliers which consist of some different excess heat suppliers, a gas boiler and an electric boiler. The five groups are in this study defined as the main suppliers of DH in the municipality of Aalborg and will be the main focus of this study regarding heat production. Their respective share of heat they are supplying to the DHS in Aalborg municipality can be seen in Figure, 7.3, below.

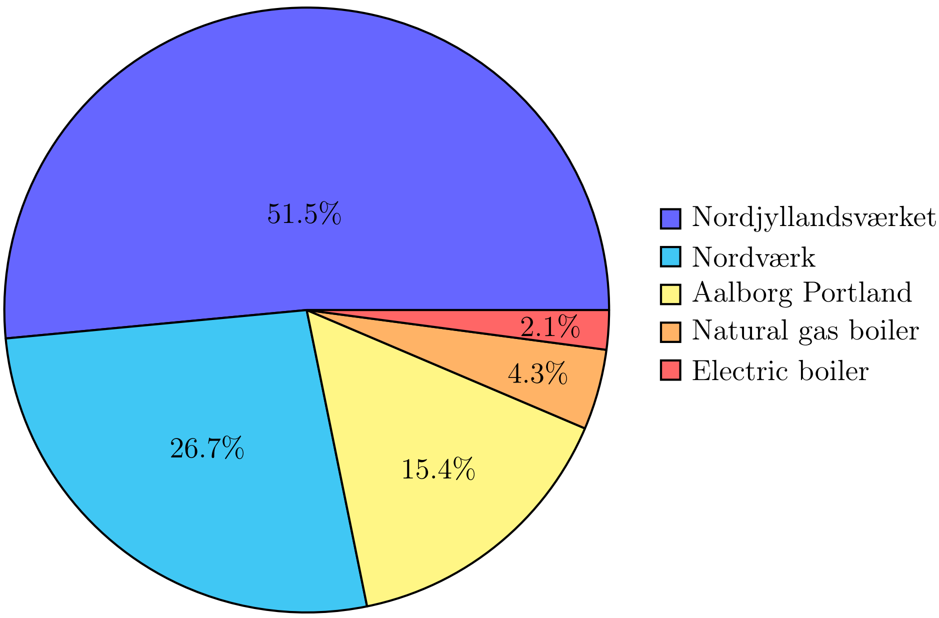

Figure 7.3. Pie chart representing the share of DH from each supplier

As shown in the Figure above, 7.3, Nordjyllandsværket is the main supplier of DH, with Aalborg Portland and Nordværk supplying almost the same amount.

Each DH supplier will be presented and elaborated further in the following Sections. Reports and articles were the primary literature for describing the case of Aalborg municipality, but an interview was also held with Silas Alvin Hupfeld, who is the team leader of strategic energy planning at Aalborg Forsyning, to gain a better insight into the DHS of Aalborg municipality. An overview of the interview can be found in Appendix A.

Nordjyllandsværket

Nordjyllandsværket is a CHP plant located in Aalborg municipality near a town called Vodskov, and it is owned by Aalborg Forsyning. The plant consists of a production unit, Block 3, which was commissioned in 1998, that can produce electricity and heat. Block 3 has an electrical capacity of 383 MW (net) and a maximum DH output of 420 MJ/s [Aalborg Forsyning, 2019]. Block 3 at Nordjyllandsværket holds the world record for fuel utilisation efficiency among coal-fired units [Aalborg Forsyning, 2019]. With an efficiency of up to 91% in combined production and 47% in pure electricity production, Block 3 utilises fuel about 20% better than older coal-fired plants. The primary fuel is coal, but fuel oil is used for boiler startup and as an alternative fuel [Aalborg Forsyning, 2019].

As mentioned in the section above, coal is the main fuel that is used at Nordjyllandsværket and to a much lesser degree fuel oil, gas oil, and propane. The amount of fuel from each fuel type that was used for the years 2015-2019 is listed in Table 7.2 below [Aalborg Forsyning, 2019].

Table 7.2. Fuel consumption and energy content

Year	Coal (ton)	Fuel oil (ton)	Gas oil (ton)	Propan (ton)	Total Energy (GJ)
2015	556,360	1,569	334	1	13,376,660
2016	705,623	778	308	0	17,109,610
2017	492,896	988	280	0	12,125,650
2018	530,061	688	143	0	12,967,145
2019	332,621	358	460	1	8,117,536

The reason for the relatively low usage of coal for the year 2019 was because of a fire under generator Block 3, which required significant repair efforts and resulted in a total downtime of approximately 7 months - from mid-May to early December. During this period, Nordjyllandsværket provided the necessary DH via the electric boiler and heat centres at Gasværksvej in Aalborg [Aalborg Forsyning, 2019].

Nordværk

Nordværk is a waste management facility that is situated at Troensvej in Aalborg, Denmark and serves as a component of the region's integrated solid waste management infrastructure [Nordværk, 2023a]. Nordværk functions as a waste incineration plant that converts waste into energy in the form of either electricity or heat with its two ovens. The heat is sold to Aalborg Forsyning for the DHS in Aalborg, while a small portion of the electricity generated is used onsite and the rest is fed into the national power grid [Nordværk, 2023a]. Nordværk is approved to incinerate up to 250.000 tons of waste per year. The facility has two furnace lines, with the newest furnace line being put into operation in 2005 with a capacity of 22,5 tons per hour, with a calorific value of 10,7 GJ/ton in the waste [Nordværk, 2023a]. This corresponds to a capacity to process approximately 180.000 tons of waste annually on this line. The second furnace line in Aalborg was commissioned in 1991 and has a capacity of approximately 11 tons per hour with a calorific value of 10,7 GJ/ton. The facility was upgraded in 2007 and has been approved for operation approximately eight months per year since 2018. The utilisation of the waste's calorific value is nearly 100% for the facility [Nordværk, 2023a].

Aalborg Portland

Aalborg Portland was established in 1889, and it is the only cement manufacturer in Denmark, operating its cement plant located in Rørdal, east of Aalborg City [Portland, 2022b]. Aalborg Portland directly employs 350 people at their production facility in Aalborg. Cement production is characterised by its high energy demand, with high temperatures needed to produce the cement clinkers. Both grey and white cement are produced at Aalborg Portland, and the manufacturing processes are almost identical, differing primarily in kiln configuration [Portland, 2022b].

Natural gas boiler

As seen in Figure 7.2, then is natural gas the third most used fuel type to produce heat in the DHS of Aalborg municipality. This is often used during peak load hours or when Nordjyllandsværket is shut down because of maintenance A.

Electric boiler

As mentioned earlier in this chapter, there are also suppliers of DH that only deliver a small portion to the DHS, and these are mainly the crematorium, IKEA Aalborg, the two sewage water treatment plants, and an electric boiler. The amount of heat supplied by each supplier in the *Electric boiler* category can be seen in Table 7.3 below.

District heating suppliers	Heat in GJ	Heat in kWh
Electric boiler - Norbis Park	146.074	40.576.111,1
Kyoto - Norbis Park	599	166.388,88
Renseanlæg Øst	8.726	2.423.888,88
Renseanlæg Vest	4.978	1.382.777,77
Aalborg Crematorium	5.088	1.413.333,33
Ulsted Biogas ApS	6.338	1.760.555,55
IKEA Aalborg	7.545	2.095.833,33
Other Heat Providers	994	276.111,11

Table 7.3. DH suppliers and their supply of heat in GJ and kWh

Of all the suppliers in this category presented in the table above, 7.3, the electric boiler at Aalborg Forsyning's *Norbis Park* is the main supplier of heat, contributing 81% of the 2.1% in the group. Similar to the natural gas boiler, the electric boiler is primarily used during peak load hours A. Additionally, it is utilised when electricity prices are very low in Denmark, allowing it to produce heat more economically compared to other more expensive production units A.

District heating infrastructure

This section will present the DH infrastructure in the municipality of Aalborg. In this study, the infrastructure will be the length of the DH pipe and the number of pump stations that are used in the DHS. In 2020 Aalborg Forsyning reported that they had 1.803,7 km of DH pipes in the municipality of Aalborg at the end of 2020 [Aalborg Varme A/S, 2020]. The amount of DH pipes in Aalborg municipality has been increasing steadily yearly, where in 2016 there were 1.592 km of DH pipes. The DH pipes are divided into three categories: transmission pipes, distribution pipes, and consumer pipes [Aalborg Varme A/S, 2020]. To pump the hot water around the municipality of Aalborg, Aalborg Forsyning has 69 pump stations to this. The number of pump stations has also been increasing yearly, with 64 pump stations in 2016 [Aalborg Varme A/S, 2020].

7.3 Future plans for the district heating system of Aalborg municipality

The current plan is that Nordjyllandsværket is supposed to close by 2028. This will then leave a gap in the supply of DH in Aalborg municipality. How this gap will be filled out in the future will be presented in this Section.

According to Søren Gais Kjeldsen, CEO of Aalborg Forsyning, and Jesper Høstgaard Jensen, technical CEO of Aalborg Forsyning Kjeldsen and Jensen [2024] then is some of this *"gap"* is supposed to be filled with an increase of excess heat utilisation. The plan is when Nordjyllandsværket closes in 2028, the share of excess heat will be increased to about 40% [Kjeldsen and Jensen, 2024]. This extra excess heat will come from an increase of excess heat from the sewage water treatment plant, Renseanlæg Vest, and also include excess heat from a Power-to-X (PtX) facility. But some of these projects are in danger of being cancelled, because of the price ceiling. Initially, the price cap caused Aalborg Forsyning to pause the 20 MW heat pump project at the wastewater treatment plant Renseanlæg Vest [Aalborg Forsyning, 2023b]. This project is estimated to cost 195 million Danish kroner [Kjeldsen and Jensen, 2024]. Another investment of 50 million Danish kroner at the Renseanlæg Øst was so far along in the process that it could not be stopped, but it would, in turn, result in a financial loss for Aalborg Forsyning [Kjeldsen and Jensen, 2024].

As mentioned above, then is a new PtX facility called Fjord PtX being planned and it will convert electricity into jet fuel. This is achieved by first splitting water into hydrogen in a 300-400 MW electrolysis plant, and subsequently converting the hydrogen into jet fuel through a synthesis process with captured CO_2 [Aalborg Forsyning, 2024a]. Annually, the facility is expected to produce up to 110 million litres of aviation fuel [ibid.]. The facility will also generate a significant amount of surplus heat, which will be 200 GWh of excess heat from the facility yearly after 2028, equivalent to 10% of the annual heat production in Aalborg municipality [Aalborg Forsyning, 2024a].

Aalborg Forsyning has also entered into a contract with the Swiss company MAN Energy Solutions regarding a new major production unit, which is a seawater heat pump with a capacity of around 132 MW and will supply circa 1/3 of DH in Aalborg municipality [Aalborg Forsyning, 2023c]. This will help to replace the coal-based DH from Nordjyllandsværket when it shuts down in 2028. The facility in its entirety will consist of three heat pump units of 44 MW each, each of which is the world's largest based on natural refrigerants [Aalborg Forsyning, 2023c]. Overall, it is one of the world's largest seawater heat pumps, which will be located at Limfjorden in Norbis Park. The facility will account for almost one-third of the heat production in Aalborg Forsyning, while the rest will come from sources such as electric boilers, heat pumps, surplus heat from waste incineration at Nordværk, and local businesses, among others [Aalborg Forsyning, 2023c]. These other heating production units and excess heat suppliers will be explained further below.

Besides the seawater heating pump, Aalborg Forsyning, as mentioned in the section above, is also building three electric boilers at their site at Norbis Park, Aalborg. The three electric boilers will have a total capacity of 150 MW and are expected to account for approximately 16 % of the heat production in Aalborg Forsyning [Aalborg Forsyning, 2024b]. The plan is for the electric boilers to be operational by 2025.

Lock-in in relation to the case of Aalborg 8

8.1 (Carbon) lock-in in relation to the case

To understand how the present situation of the case is to be understood in the context of (carbon) lock-in theory, the described phases of it, as presented in 4.1, are used to explain how the DHS in Aalborg and its contributors came to be, how they have established themselves, and an explanation on why these paths in the past were chosen.

As Unruh [2000] stated, TICs arise because of large technological systems, in this case, heat production (primary and by-product), distribution and end-use. It is not to be understood as a set of separate technological *"artefacts"* but needs to be seen as a complex system of technologies integrated into a social context of public and private institutions. Here the most important aspects of Unruh [2000] that can lead to a locked-in TIC are repeated. A TIC develops through *"a path-dependent, co-evolutionary process involving positive feedback among technological infrastructures and the organisations and institutions that create, diffuse and employ them"* Unruh [2000]. This was already exemplified prior for the waste incineration in Gothenburg presented in Section 4.1. Once established, the TIC is difficult to displace creating what is called *"inertia"* against changes that challenge the current practice. By that, it can lock-out alternative technologies, even if the alternatives offer improvements towards new circumstances like newly introduced policies, goals or targets the established TIC can not.

8.1.1 Involved stakeholders

To assess if and to what extent a lock-in exists the relevant aspects are checked for the case of the DHS in Aalborg municipality. First, the current main stakeholders affected and involved in the Aalborg DHS are to be introduced to understand their position and role. In lock-in situations, the forces that can form a TIC can be categorised into three groups. Those are the technological, institutional and social forces, each of them playing its role and stakeholders taking part in at least one of them if not several.

Legislation (EU and Danish national Government)

The government has power through laws and legislation which Aalborg municipality needs to comply with. Their power and influence are therefore high, they are taking an indirect influence on the frame for the development of the future DHS in Aalborg municipality. They affect development through laws, legislation, tariffs, taxes and subsidies which all are to be expected done according to the national energy strategies.

Aalborg Municipality

The municipality of Aalborg owns the DHS operator Aalborg Forsyning. There is cooperation in communicating needs and interests. The municipality influences decisions for the DHS and needs to reach its own defined goals and targets guided and demanded by the frame the Danish government creates and should ultimately act in the interest of its citizens. In this case related to supplying heat to consumers in a reasonable manner and in accordance with existing law.

Aalborg Forsyning

As stated, the DHS operator Aalborg Forsyning is a private company owned by the municipality and thereby has to follow the strategies set by the municipality and indirectly the national regulatory decisions. Their task is to manage the balance between supply and demand in the DHS by either increasing or reducing heat in the system at any time and further maintaining and developing the core system. In recent years they have developed plans and projects for producing heat from new heat sources on their own. They own the Nordjyllandsværket facilities yet were not in charge of the construction but bought the plant from Vattenfall in 2015 [Vattenfall, 2018]. They played a key role in the past, nowadays their influence on the system and its development is more apparent as they are in charge of some new developments in heat-producing infrastructure for the DHS themselves. They further have the task of managing, maintaining and developing the DHS aligned with the municipality's and consumer's interests as well as possible.

Consumers

The consumers are many different groups of people who receive and use the DHS heat in different ways at different times. But their overall consumption shapes the demand and generally, an interest in steady, stable supply at a reasonable price is assumed. Otherwise, they could also switch to individual solutions which is deemed environmentally less beneficial because of higher amounts of resources being needed than the common solution a DHS can provide in a case like Aalborg being a city of a size big enough to run a DHS [Balode et al., 2021].

Nordværk and Aalborg Portland

As described in Section 7.2 two excess heat suppliers contribute significantly to the DHS. They share a mutual interest in the supply as they are compensated for the excess heat provided even though it is not their main purpose as they are handling waste and producing cement. They both have a considerable amount of influence as their cooperation with Aalborg Forsyning is deemed beneficial for both sides and the DHS operator needs to incorporate them in their daily supply plans.

Other actors

Aalborg Wastewater treatment facility, data centres, crematory and others. These actors have a small input or could have input into the future development and have an economic interest in the future DH supply system of Aalborg. A few stakeholders have been mentioned but these can be plentiful and do not have any real power.

When excluding the indirect influence of the legislator and the less significant "other actors" the five main stakeholders have a substantial direct influence on the DHS in Aalborg. The development without considering these five stakeholders seems unreasonable. Aalborg Forsyning is in charge of the development of the DHS so any change has to be evaluated and planned by them. Aalborg Municipality is the link to ensure accordance with legislation and public interest and has developed the strategies and goals for the future. The excess heat suppliers are the companies that focus on their own business whilst partaking in the DHS operation. They are not the main stakeholders but have a high influence due to their considerable share of provided heat and interest from the legislator to be included. The consumers are included here but their influence is more apparent if the service of heat supply is not fulfilled adequately. They are still included as there would be no demand or reason to operate a DHS without them.

8.1.2 Lock-in phases in relation to the case

The path dependency from the past and a potential TIC in the Aalborgs case is to be analysed below in steps that resemble the phases of TIC establishment from Section 4.1. This is both done from a historical and future perspective.

Phase 1: The initial event setting off the development

When taking into consideration the description of carbon lock-in by Unruh [2000] and for the energy sector specifically by Goldstein et al. [2023], the dominance of carbon-based heat supply in Aalborg DHS was not in danger of being challenged by any more competitive or decentralised solutions before the 1990s. The energy crisis in the early 1970s can be seen as a fairly unpredictable outside event giving an impulse for change of plans for the means of heat production and supply not being too reliant on oil.

Henrik Lund's publication on Renewable Energy Systems is used to contextualise changes to the biggest heat suppliers of the Aalborg DHS. Even though he focuses on the feasibility evaluation of energy projects and introduces his choice awareness theory, his often first-hand experience and detailed description of past developments serve as a good background to reflect on path dependency and a potential lock-in in the current DHS. Lund [2009] describes the dynamics that led to the continued implementation of coal-based heat after the power station Nordkraft was planned to shut down in 1999 after an, as Lund calls it, "unfortunate lifetime" of being converted to an oil-fired heating plant in the early seventies right before the oil crisis and being converted back to coal later. After the decision to shut Nordkraft down, he also describes the decision-making process for the substitute of Nordkraft which later was decided to become what is Nordjyllandsværket. In his descriptions, he lines out how the energy company influenced the decision-making process in the city council as well as the clear inertia against proposed alternative solutions (in this case decentralised heat supply by small CHPs and increased insulation on the consumer side). The main reason for change at the time namely the desired increased independence from international and at the time unstable oil supplies and high prices was yet not addressing concerns about carbon or other environmental impacts the way it is discussed nowadays.

"The case of the Nordjyllandsværket in the mid-1990s first the Danish Parliament had decided on an energy policy, called Energy 21, according to which no new coal-fired power station was needed. Instead, the Parliament had decided to implement electricity savings and expand the number of small CHP plants. Still, the power companies, supported by the minority government, succeeded in implementing another coal-fired power station" [Lund, 2009].

During the 1990s the current main suppliers for DH in Aalborg were introduced the way it is structured today. Since then it has experienced some changes but the main suppliers did not change significantly. This is picked up again in phase 6.

Phase 2: Positive feedback loops around elements of a new systems

Since the 90s excess heat utilisation has been practised in the DHS by including supply from Nordværk (then RenoNord) and Aalborg Portland. This is due to beneficial cooperation in the interest of the excess heat suppliers and the DHS operator as there is monetary compensation for supplying and it provides flexibility to the heat management in the DHS. Further, the Nordjyllandsværket facilities can shift the share of heat and electricity cogeneration internally. So if there are high electricity prices producing more electricity for the market is more profitable and possible due to the DHS operator being able to substitute for the lack of heat supplied by using the excess heat suppliers. This presents a positive feedback loop as more excess heat in the system becomes favourable to all suppliers and Aalborg Forsyning, increasing efficiency for all suppliers. Nordværk has increased the burning of more waste over time and expanded capacity. There might be a similar situation of reliance on a decreasing supply of fuel pending like the Gothenburg case. Even though Aalborg DHS does not rely on waste incineration as much. Yet Nordværk is also already importing waste from other places in Denmark and from other countries which can be partially attributed to a consolidation of waste incineration in other municipalities [Nordværk, 2022]. Aalborg Portland increased excess heat supply because of technical opportunities and the option to become more efficient.

Phase 3: A network effect

The system was expanded to currently 1.803,7 km of DH pipes in the municipality of Aalborg at the end of 2020 and also a cooling system was introduced [Aalborg Varme A/S, 2020]. The integration of the DHS has continuously progressed and plans to utilise different heat sources are explored. Further, the integration of a few more consumers has become easier due to excess capacity by utilising diverse suppliers that are flexible in their supply of heat. The overall operations are also already routine and Aalborg as a city is big enough consumer-wise to make use of the high efficiency that a DHS brings with it. This makes it very accessible for new consumers in the city of Aalborg to join the system with fairly low individual risk and financial burden compared to individual solutions. Smaller and less dense places face less favourable conditions for implementing DH and are also comparably more affected by individuals opting for individual heating solutions. It can thus be stated that a network effect has developed and works in favour of the stakeholders involved.

Phase 4: *"lock-in"* of the most competitive practices occurs

When Nordjyllandsværket was built it was lauded to be a highly efficient, competitive and modern coal-fired cogeneration heat and electricity plant. Aalborg Forsyning has made use of that since its implementation in 1998. The described increase of excess heat being supplied by Nordværk and Portland is also due to the practice showing favourable competitiveness for them. It needs to be stated that by the nature of a DHS to have a regional monopoly in wide heat distribution and the legislators asking for more energy efficiency as well as cogeneration plants in DHS as a standard requirement by including excess heat and a specific amount of cogenerated heat EU [2023].

Phase 5: Entrance barriers

The technologies and practices were amplified and supported by the positive feedback loops and led to a system that disadvantages every other technology that is not "locked-in" due to high entrance barriers, especially in the investment-intensive built infrastructure sector. CHP electricity and heat cogeneration at a scale like Nordjyllandsværket was without an alternative for a long time due to high initial investment costs that had to be broken even. Replacement of the same capacity is costly. Further, the existing technology is heavily optimised and its practice is well known creating more advantages for the existing structures. Taking into account the description by Lund [2009] on how the decision for the coal-fired power plant in the 90s was taken against several attempts by informed consumers to introduce other more decentralised solution alternatives for heat supply and efficiency it could be claimed that there was a much more "locked-in" situation apparent than what it is today. The DHS has developed since then as it is described so far but when deciding to build the main contributing heat supplier Nordjyllandsværket the municipality was faced with resistance in the decision-making process. This was due to the public opinion having developed since the seventies and carbon as well as other environmental concerns having become a necessity for the public. Some individuals tried to widen up the available choices by informing about other options which was not only turned down but also criticised by the municipality. Even though these proposed options excluding coal were presented, the decision for Nordjyllandsværket was taken. Against the proposed alternatives for the plans on the grounds of environmental concerns and technological alternatives, it was decided.

"Nothing was said about the background for the desired location in terms of environmental impacts, no environmental assessment of any part of the high-voltage transmission lines that would result from the Nordjyllandsværket was included, and the analysis did not treat the question of cleaner technology [Lund, 2009]."

Here the the criteria of a broader "lock-in" can be observed with a clear inertia for maintaining practices and sticking to known and used, just more efficient technologies (representing dynamics of the final phase). This can be interpreted as a successful combined effort of the TIC to exclude better solutions to a problem that was not apparent in the years earlier in the development path when the main concerns were not about carbon and or environmental aspects 6.1.

Considering that Unruh [2000] and Corvellec et al. [2013] state that end-of-life of facilities or a crisis can be the opportunity to change and break out of existing "lock-ins" the decommissioning Nordjyllandsværket and subsequent substitution by technological alternatives like heat pumps, electric boilers and increased use of excess heat, the inertia that was faced in the 90s seems to have dissolved due to feasible alternatives having further developed and strategies having shifted its focus. Also a better understanding of the entailed impacts and public availability of relevant information leading to legislation having lined out impact mitigation by (mainly) carbon reductions can be seen as a factor here.

Phase 6: The *"lock-in"* works as an attractor

The dominant technology became the easiest possible solution supported by the elements that made up the TIC. In this case, it is the DHS and its different suppliers being more attractive than individual solutions. It can be stated that the TIC has existed more entrenched in the past. Other technologies had less chance to break into the as the DHS operator did not need to move away from the existing system since the 90s. Aalborg Forsyning also knows how to handle the process and is open to smaller expansions and developments. Now that the main heat supplier is nearing the end of its lifetime after 30 years of operation, the opportunity and reason to change have been taken up. This does not take away from the DHS still being the easiest-to-access source of heat in Aalborg. As long as the newly introduced heat supply works out as intended, the attractiveness of the network effect the DHS would prevail as the other parts and the service of the system technically stay the same.

Phase 7: Signs of established inertia

Looking at the past and planned future developments, there seems to have been a carbon lock-in before in the Aalborg DHS. The future seems to leave this situation behind because of the utilisation of innovative and favourable technologies concerning the strategies and goals laid out by the legislators today. As the realisation of the substituting technologies is progressing and already being built there is little concern that Nordjyllandsværket will not leave the DHS in 2028.

Shifting the focus away from Nordjyllandsværket and onto the excess heat providers becoming more interesting for the DHS operator. Their position is mostly unchanged in the DHS except for the option/need to supply some more excess heat than before. Very progressive plans for heat pumps exist and focus on decarbonisation. Whilst other DHS are just starting to look at cogeneration and excess heat utilisation, the path of decarbonisation is already being followed and brought into reality. This is where the question of excess heat utilisation becomes more important as it might be the last remaining source of fossil-based heat in the Aalborg DHS. The definition of burden allocation might become a problem as it does not seem clear who has to take responsibility for the emissions and impacts. EU legislation encourages the utilisation of excess heat in DHS and has laid out a path for the coming years to increase its use [EU, 2023]. Aalborg seems to be more advanced in the integration of such options than other European DHS, which is elaborated in Section 8.1.2. Yet with the newly integrating technologies being electricity-based and the Danish government planning to produce emissions-free electricity, the excess heat providers become the suppliers with the highest carbon contribution. Under the current circumstances considered this could pose an issue and the responsibility for it is discussed in Section 11.5 as this might pose a situation that here shall be named "partial prolonged lock-in". Also, the price ceiling (Prisloft) introduced to stabilise the heating prices through the recent energy crisis is inhibiting further development. This does not necessarily need to be seen as a contributor to lock-in but hinders innovation towards the stated goal of decarbonising.

The former lock-in seems to be currently dissolved and a full lock-in has been avoided due to changes in technological preference, proposals by experts from the academic and engineering fields, outside factors, and electricity markets not favourable for CHP. energy independence, and climate goals. The remnants of a full carbon-based complex are leaving the system in the near future and will be replaced. Suppliers of excess heat present secondary carbon-based heat suppliers and are not acknowledged by the DH-system operator to be fossil-based primary producers of heat. This means that the goal set out by Aalborg Forsyning to be fossil-free by 2030 currently should not be in danger even if excess heat suppliers are still relying on fossil fuels for their primary products.

The case of Aalborg in comparison to other European district heating systems

During the research into the current set-up and the plans for Aalborg DHS, it became apparent that it has been continuously worked on. This means that it uses fairly new technologies and is also approaching the task of distributing DH in a progressive manner compared to other DHS in European cities. In other countries, DHS is often still a primary heat supply system without cogeneration options and often the utilisation of excess heat is only used to a limited extent if even implemented [Jeandaux et al., 2021] [Fontaine and Rocher, 2024]. An often observable already-used technology is the waste being incinerated or used for biogas in recent years Jeandaux et al. [2021]. Yet the utilisation of excess heat from industrial activities is not being done, has been investigated or is just in the process of being introduced. In the context of the EU [2023] the aspect of cogeneration and excess heat utilisation presents good opportunities and is mandated to make more use of already produced energy from other processes or flexible power plants like CHPs. When looking at the Aalborg case and its plans to become independent of fossil fuels in 2030, the goals and proceeds of other DHS seem a bit more behind. As the directive has been created for the whole EU and needs to incorporate the reality of DHS existing in very different environments and national circumstances, the Aalborg case can be deemed a front-runner/pioneer with their currently proceeding plans and commitments. This might stem from the historical background of switching towards more DH already in the 70s to become more energy-independent from oil and/or gas. By that, an expertise in the field has developed over decades and the social-political context does not see it as a new or uncertain field anymore. It could be argued that the current baseline can serve as an orientation for others to not become subject to CO_2 blindness in their decisions for how to develop a DHS. Further, the case of Aalborg's future development and how it is playing out in the next coming years could serve as an example to other operators to decarbonise or increase efficiency (depending on how developed the systems currently are) or to learn from experiences that will be made with the incorporation of these new technologies.

8.2 Sub-conclusion for lock-in in relation to the case

Section 8.1.1 introduced the main stakeholders involved in the DHS of Aalborg municipality, highlighting their roles and influence. Aalborg municipality, Aalborg Forsyning, and key excess heat suppliers like Nordværk and Aalborg Portland play pivotal roles in shaping the DHS. Consumers, while having less direct influence, are important for sustaining demand. Legislation from both the EU and the Danish government provides the overarching framework within which these stakeholders operate. Understanding these stakeholders is necessary for assessing potential lock-in situations and identifying opportunities and barriers for future DHS development in Aalborg municipality. The analysis of Aalborg municipality's DHS in Section 8.1.2 reveals a historical carbon lock-in driven by past energy policies and reliance on coal and excess heat. However, with the imminent decommissioning of Nordjyllandsværket and the introduction of new, sustainable technologies, Aalborg municipality is transitioning towards a decarbonised future. Despite challenges such as managing the carbon impact of excess heat suppliers and price ceilings inhibiting innovation, the shift indicates a move away from a carbon-intensive system, aligning with current climate goals and technological advancements. From Section 8.1.2 it can be concluded that Aalborg municipality's DHS stands out for its progressive approach, utilising new technologies and emphasising cogeneration and excess heat utilisation, unlike many other European DHS which rely primarily on traditional heat supply methods. Plans to decarbonise by 2030 position it as a pioneer in the field, offering a model for other cities to enhance efficiency and sustainability in line with the EU Efficiency Directive. This case highlights the importance of overcoming carbon lock-in through innovative strategies and collaboration among stakeholders.

9 Life Cycle Assessment of Aalborg's District Heating System

The overall structure of the LCA model will be briefly outlined in the following section and further expanded upon in Section 9.3. The LCA tool SimaPro (version 9.5.0.1) and the database Ecoinvent (version 3.9.1), [Wernet et al., 2016], are utilised for the modelling and background data for the LCA.

This LCA study will, as explained in Chapter 7, take the point of departure in the DHS in the municipality of Aalborg, Denmark. This study focuses on incorporating a temporal dimension into the LCA of the DHS, as detailed in Section 6.2.1. In this study, three different scenarios are selected for use within the LCA model. The first scenario is a baseline of the current DHS of Aalborg municipality where environmental impacts are allocated to the excess heat based on the method outlined in Section 6.2.2. The second scenario is the same as the baseline, but it does not allocate any environmental impacts to the excess heat. Lastly, a 2030 scenario is included, which will be based on the future heat-producing facilities in Aalborg municipality. All scenarios are modelled and further elaborated in Section 9.3.

9.1 Framework for the Life Cycle Assessment model

This LCA study will be performed in compliance with the following standards from the International Organisation for Standardisation (ISO) regarding doing LCAs: ISO 14040:2008 Organisation [2006a] and 14044:2008 Organisation [2006b].

9.2 Goal and scope of the study

The goal of this study is to conduct a comprehensive assessment of the environmental impact associated with utilising excess heat in the DHS of Aalborg municipality, aiming to fill the existing knowledge gaps in this area as presented in 2.5. The intended application of this study is therefore to gain deeper insights into the environmental implications of such practices when utilising excess heat based on different scenarios.

Target audience

The beneficiaries and users of this study include heat utility and distribution companies, the scientific community, as well as practitioners and researchers involved with LCA.

9.2.1 Functional/declared unit

This Section will present and define the declared unit that will be utilised in this study of the DHS in the municipality of Aalborg.

The declared unit will be based on the product category rules (PCR), *PCR - 2007:08 version 4.2 - Electricity, steam and hot/cold water generation and distribution* that is used for EPDs for DH and more. According to the PCR, then shall the declared unit be defined as the following in an EPD: One kWh of steam or hot/cold water generated and thereafter distributed to the customer. Since this study will focus on heat from a DHS delivered by hot water, then will the declared unit be the following:

The declared unit in this study is defined as 1 kWh of hot water produced and thereafter distributed to the customer in the municipality of Aalborg.

The declared unit, that is stated and defined above, will be utilised in Section 9.3 for all scenarios throughout the study.

9.2.2 System boundary

This study utilises the system boundaries based on a cradle-to-grave approach. This approach was chosen for the study as it allows for a thorough examination of the entire life cycle of the heat that is utilised in the DHS in the city of Aalborg. This LCA study will include the entire life cycle of the DHS, from raw materials and fuel extraction (cradle) to end-of-life disposal (grave). This perspective ensures that all significant environmental impacts across the entire life cycle are accounted for, providing a thorough and accurate assessment of both the system's overall impact and also for each heat supplier. An overview of the studied system can be seen in figure 9.1

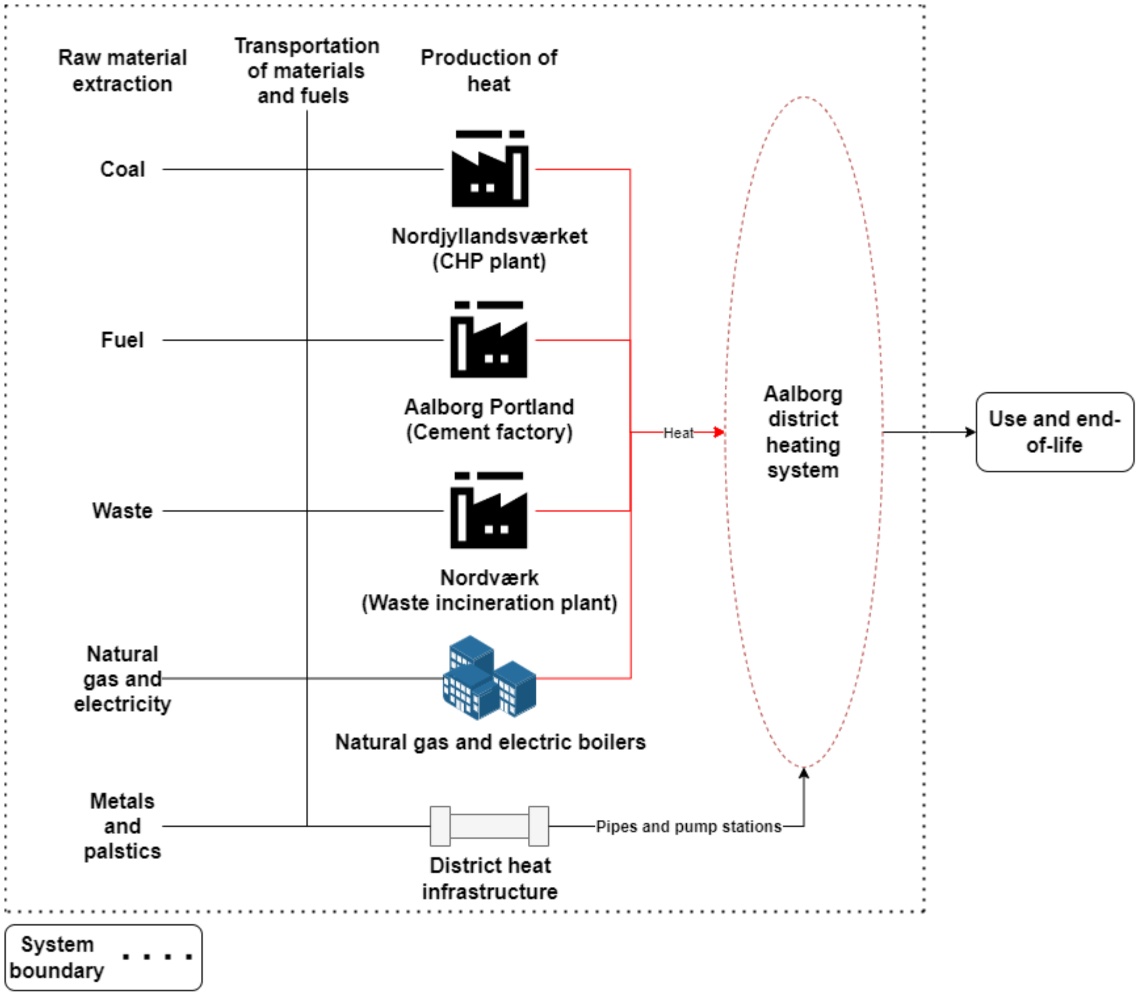

Figure 9.1. The system boundary of the studied DHS in Aalborg municipality

The Figure, 9.1, illustrates the system boundary for the DHS in Aalborg municipality, highlighting the various components and processes involved in the production and distribution of DH. Included within the system boundary are raw material extraction (such as coal, fuel, waste, natural gas, and electricity), and metals and plastics. The transportation of these materials and fuels to production sites is also included. Heat is produced at several facilities: Nordjyllandsværket a CHP plant using coal, Aalborg Portland a cement factory using different fuels, Nordværk a waste incineration plant using waste, and additional natural gas and electric boilers. The heat generated is distributed through a DH infrastructure that consists of pipes and pump stations, leading to the Aalborg DHS, which delivers heat to end-users. The system includes the production and distribution phases but excludes the use phase and end-of-life processes. These phases are considered outside the system boundaries and are not included in the analysis. This is depicted by placing this box beyond the dotted line, marking the boundary of the system as seen in Figure 9.1.

9.3 Life cycle inventory

This section will detail the various input and output processes utilised in the different scenarios of this LCA study. By presenting these processes, the aim is to provide a clear understanding of how each scenario operates and contributes to the overall assessment.

9.3.1 Baseline

The baseline in this study will reflect the current production of one kWh of heat in the form of hot water in the current DHS in the municipality of Aalborg for the year 2023. As explained in Section 3 and further elaborated in Section 6.2.1, then will this study include a temporal aspect, and therefore will the baseline scenario stretch over the year 2023, and the environmental impacts will be declared on an hourly level.

Heat suppliers

To model the DHS for Aalborg municipality, the various heat suppliers are modelled. A detailed description of this modelling process is provided in the following sections.

Nordjyllandsværket

As described in Section 7 the main heat supplier in the Aalborg Municipality DHS is Nordjyllandsværket. To model the production of heat from this supplier, the dataset "Heat, district or industrial, other than natural gas DK| heat and power co-generation, hard coal | Conseq, U" is used. To make the modelling more accurate, this dataset is modified to better match the actual production of heat from Nordjyllandsværket. Whereas the chosen dataset only uses coal as fuel input, Table 7.2 shows that Nordjyllandsværket also uses fuel oil and gas oil. As a result of this, processes for fuel oil and gas oil are added as inputs. The data used to model the amount of fuel needed to produce one kWh of heat is based on 2018 data [Aalborg Forsyning, 2019]. The source for this data also declares the fuel usage for 2019, however, this year is an outlier due to parts of the CHP being inoperative for 7 months, resulting in the 2018 data being chosen as it is the most recent available data [ibid.].

The coal is modelled using the dataset "Hard coal Europe, without Russia and Turkey| market for hard coal | Conseq, U". As the Ecoinvent dataset used to model the production of heat uses MJ as the unit, the amount of fuel needed is likewise calculated for the production of 1 MJ. This is done using the total amount of fuel used by Nordjyllandsværket, divided by the total energy production. An example of this can be seen below:

$$\frac{530,061,000\,\text{kg}}{8,885,703,600\,\text{MJ}} = 0.05965\,\frac{\text{kg}}{\text{MJ}} \tag{9.1}$$

The fuel oil is modelled using the dataset "Heavy fuel oil RER| market group for | Conseq, U". The choice of heavy fuel oil instead of e.g. light fuel oil is a conservative assumption, however, as this fuel type only makes up 0,13% of the fuel in Nordjyllandsværket, any uncertainties are deemed insignificant. The gas oil is modelled using the dataset "Diesel RER| market group for | Conseq, U" as no dataset specifying gas oil could be found in the Ecoinvent 3.9.1 database. As this fuel type only makes up 0,03% of the fuel used in Nordjyllandsværket, any uncertainties are deemed insignificant.

In the Ecoinvent dataset chosen to model Nordjyllandsværket, 52% of the CHP production is allocated to electricity, while for the actual CHP plant, this number is 56% [Aalborg Forsyning, 2019]. As such, this number is edited in the dataset to match the production of Nordjyllandsværket, which means that 56% of the total environmental impact from producing 1 kWh of heat is allocated to electricity production, and therefore not included in the impact of the production of heat.

The processes and the modified values can be seen in the table below:

Ecoinvent process	**Original value**	**Modified value**	**Unit**
Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, hard coal | Conseq, U	1	1	MJ
Hard coal {Europe, without Russia and Turkey}| market for hard coal | Conseq, U	0,13470	0,05965	Kg
Heavy fuel oil {RER}| market group for | Conseq, U	0	0,00008	Kg
Diesel {RER}| market group for | Conseq, U	0	0,00002	Kg
Electricity, high voltage {DK}| market for electricity, high voltage | Conseq, U	-0,30122	-0,32169	kWh

Table 9.1. Modified processes for the modelling of Nordjyllandsværket

Nordværk

The waste incineration plant, Nordværk, which is further described in Section 7.2, is modelled using the dataset "Municipal solid waste DK| treatment of municipal solid waste, incineration | Conseq, U" from Ecoinvent 3.9.1. This process is chosen as no site-specific data from Nordværk regarding the waste composition at Nordværk has been obtained. Therefore, It is assumed that this process is an adequate way of representing an average mix of solid waste incinerated in a municipal incineration plant in Denmark.

The Ecoinvent process represents the environmental impact of incinerating 1 kg of waste. However, to get a more representative result showing the specific environmental impact of the energy production at Nordværk, production data from the waste incineration plant is used. This data includes the total heat and electricity production on a daily level, as well as the amount of waste needed to produce the energy. The amount of waste needed to produce 1 kWh of heat at Nordværk is calculated by dividing the total yearly amount of waste incinerated in 2023 by the total yearly heat production.

However, as the Ecoinvent process for modelling the waste incineration uses kg as the unit describing the amount of waste, while the Nordværk data uses m^3, the Nordværk data needs to be altered to match the Ecoinvent process. To convert the Nordværk data from m^3 into kg, an estimation for how much waste is in one m^3 of waste is needed. According to Alabdraba1 and Al-Qaraghully [2013] there is between 120 - 200 kg of waste per m^3 in high-income countries. Based on this interval, a conservative estimate of 200 kg solid waste per m^3 is assumed. Using this number, the total amount of waste for producing 1 kWh can be calculated.

This number is used in the Ecoinvent process in SimaPro to calculate the environmental impact of producing 1 kWh of heat. However, to not allocate the entire environmental impact of waste incineration to the excess heat, the avoided production of heat and electricity is added to the process to subtract the environmental impact of these activities from the excess heat. To model the avoided production of electricity the dataset "Electricity, medium voltage DK| market for electricity, medium voltage | Conseq, U" is used.

The production of heat is modelled as substituting the heat from the CHP plant and is modelled using the process described in section 9.3.1 regarding the modelling of Nordjyllandsværket.

The processes and the modified values can be seen in Table 9.2 below:

Ecoinvent process	Original value	Modified value	Unit
Municipal solid waste {DK}| treatment of municipal solid waste, incineration | Conseq, U	1	1	kg
Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	0	-0,05437	kWh
Process for heat production at Nordjyllandsværket/CHP	0	-0,24107	kWh

Table 9.2. Modified processes for the modelling of Nordværk

Aalborg Portland

The cement-producing facilities of Aalborg Portland are producing grey and white cement products with a maximum capacity of currently 3 million tons per year. In the most recent report, the main share in produced amounts over the year falls on the grey cement (1.889.000 tons) and the white cement making up for a smaller amount (587.000 tons) [Portland, 2022a]. To establish an environmental impact factor regarding excess heat, the reported amount of supplied excess heat to Aalborg municipality (1.046.530 GJ) [Aalborg Forsyning, 2023a] needs to be allocated to these production numbers. Here it is important to differentiate between the production of grey and white cement as it is assumed that only the white cement production is recovering and supplying excess heat to the DHS [Sacchi and Ramsheva, 2017].

To model the excess heat production from Aalborg Portland the dataset "Cement, Portland Europe without Switzerland| cement production, Portland | Conseq, U" is used. This dataset is edited to reflect Danish conditions by changing the electricity input to the dataset "Cement, Portland Europe without Switzerland| cement production, Portland | Conseq, U". Furthermore, the amount of excess heat is added as avoided production of the CHP heat from Nordjyllandsværket. The excess heat per kg of white cement is calculated by dividing the total amount of the reported supply of DH by the total amount of white cement produced. This can be seen in the following calculation:

$$\frac{290.705.103\,\mathrm{kWh}}{589.000.000\,\mathrm{kg}} = 0,49\,\frac{\mathrm{kWh}}{\mathrm{kg}} \tag{9.2}$$

As this study only allocates the impacts associated with the production of the excess heat to the excess heat itself, it is necessary to know the amount of thermal energy consumed during the production of white cement. Khater et al. [2021] estimates that 5 GJ of thermal energy is consumed during the production of 1 tonne of white cement. By multiplying this value by the total amount of white cement produced, an estimate for the total heat production can be calculated. This can be seen below:

$$5\,\mathrm{GJ/t} \times 589.000\,\mathrm{t} = 2.945.000\,\mathrm{GJ} \tag{9.3}$$

The share of this thermal energy that is provided to the DHS is then used to determine the environmental impact of the excess heat. The calculation is as follows:

$$\frac{1.046.530\,\mathrm{GJ\ district\ heat}}{2.945.000\,\mathrm{GJ\ total\ energy}} = 35,54\% \tag{9.4}$$

As a result, 35,54% of the total environmental impact of producing 1 kg of white cement is allocated to the excess heat supplied to the DHS.

Ecoinvent process	**Original value**	**Modified value**	**Unit**
Cement, Portland Europe without Switzerland| cement production, Portland | Conseq, U	1	1	kg
Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	0	0,0376	kWh
Process for heat production at Nordjyllandsværket/CHP	0	0,493557052	kWh

Table 9.3. Modified processes for the modelling of Aalborg Portland

Natural gas and electric boiler

With the three main heat suppliers described above covering 93,6% of the heat demand in Aalborg Municipality, the remaining 6,4% is primarily supplied by a natural gas boiler and an electric boiler. Specifically, 4,3% of the remaining heat supply is provided by the natural gas boiler, and the remaining 2,1% is supplied by the electric boiler [Aalborg Forsyning, 2023a]. Both of these are operated by Aalborg Forsyning.

To model the natural gas boiler, the dataset "Heat, district or industrial, natural gas Europe without Switzerland| heat production, natural gas, at boiler condensing modulating >100kW | Conseq, U" is used. To modify this process to better represent the production of heat at Aalborg Forsyning, two inputs are changed. This is the natural gas and electricity inputs which are changed from Europe without Switzerland to the Danish-specific datasets. The amounts of natural gas and electricity used to produce the heat are based on the Ecoinvent dataset, as no specific data has been found for the production at Aalborg Forsyning.

The datasets and their values can be seen in the table below:

Ecoinvent process	**Amount**	**Unit**
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating >100kW | Conseq, U	1	MJ
Natural gas, high pressure {DK}| market for natural gas, high pressure | Conseq, U	0,02534	m^3
Electricity, low voltage {DK}| market for electricity, low voltage | Conseq, U	0,00108	kWh

Table 9.4. Datasets used to model the heat production from the natural gas boiler

For modelling the electric boiler no specific data could be found, and no dataset for an electric boiler exists in the Ecoinvent database. However, according to the Danish Energy Agency (DEA), the conversion of electrical energy to thermal energy in an electric boiler happens at close to 100% efficiency. As such the electric boiler will be modelled using the previously used natural gas boiler dataset, with no input of natural gas, and an electricity input corresponding to the amount of heat produced. This is deemed acceptable as the heat production from the electric boiler is a minor amount compared to the total heat demand. The processes can be seen in the table below:

Ecoinvent process	**Amount**	**Unit**
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating >100kW | Conseq, U	1	MJ
Electricity, low voltage {DK}| market for electricity, low voltage | Conseq, U	1	MJ

Table 9.5. Production of heat in electric boiler

Infrastructure

As seen in Figure 9.1, the system boundary of the study also includes the infrastructure of the DHS of Aalborg municipality. As described in Section 7 the infrastructure primarily consists of DH pipes and pump stations, and the modelling of these will be presented in this Section.

Pipes As it has not been possible to identify the exact type of pipe used in the DHS in Aalborg, the material composition is based on pipes from the Danish pipe producer LOGSTOR. This is the same pipe manufacturer Mahon et al. [2022] use in their LCA, and as such the material composition is based on data presented in their paper. According to Mahon et al. [2022] the pipes consist of steel, high-density polyurethane (HDPU) and high-density polyethylene (HDPE). Using this information, the DH pipes are modelled using the Ecoinvent datasets "Chromium steel pipe GLO| market for chromium steel pipe | Conseq, U", "Polyurethane, rigid foam RER| market for polyurethane, rigid foam | Conseq, U" and "Polyethylene, high density, granulate RER| polyethylene production, high density, granulate | Conseq, U".

The amounts of the materials are based on the total length of the DH piping system in Aalborg municipality as described in Section 7, along with the weight estimated in the paper from Mahon et al. [2022]. Using data from this paper, the weight of the pipe per kilometre can be estimated and used to calculate the total weight of the pipe in the DHS. The calculation for the total weight can be seen below:

$$\text{Total pipe length} \times \text{ton per km} \tag{9.5}$$

With 1.803,7 kilometres of pipe in the Aalborg municipality DHS and a weight per kilometre of 27,365 tonnes, the total weight is as follows:

$$1.803,7\,\text{km} \times 27,365\,\text{t} = 49.359,4\,\text{t} \tag{9.6}$$

Using data from Mahon et al. [2022] 51,4% of this weight is steel, with 29,4% being HDPE and the remaining 19,2% being HDPU. Furthermore, as the pipes are assumed to have a lifespan of 30 years the results are divided by 30 to get the impacts from 1 year only.

In the table below the processes, as well as the amount of material needed for the pipes in the DHS can be seen:

Ecoinvent process	Amount	Unit
Chromium steel pipe {GLO}| market for chromium steel pipe | Conseq, U	846	t
Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Conseq, U	483	t
Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | Conseq, U	316	t

Table 9.6. Processes and values for production of the DH pipe system

Pump station

For the modelling of the pump stations the Ecoinvent dataset "Pump station GLO| market for pump station | Conseq, U" is used. As no detailed information regarding the specific pump stations used in the DHS can be found, this dataset is deemed to be an adequate representation. The pump station in the dataset has a capacity of $644.546m^3$ and a lifespan of 70 years. It is assumed that this capacity is comparable to the capacity of the pump stations used in the DHS of Aalborg municipality.

Ecoinvent process	Amount	Unit
Pump station {GLO}| market for pump station | Conseq, U	69	p

Table 9.7. Process used to model the pump stations in the DHS

9.3.2 No allocation scenario

This scenario will be based on the baseline scenario, that is presented in 9.3.1, but in this scenario there will be no allocation of environmental impacts for the excess heat that is supplied from Aalborg Portland and Nordværk. In this scenario, the excess heat will be defined as emissions-free, which means that no environmental impacts will be allocated for the excess heat. This definition is based on the Heat Supply Act, presented in Section 1.1 and the DH declaration from Aalborg Forsyning where excess heat is viewed as being fuel-free [Aalborg Forsyning, 2023a]

Since this scenario is the same as 9.3.1, then no further processes or inputs are added. Two inputs have although been modified so that they correlate to the new environmental impact of excess heat that is used in this scenario. The two inputs that have been modified are the following: Aalborg Portland and the waste incinerator Nordværk. The way these two inputs have been modified is that the processes that have been modelled for them in 9.3.1 will be excluded in this scenario since they will have no environmental impacts at all.

The inputs of Nordjyllandsværket 9.3.1, the gas and electric boiler 9.3.1 and infrastructure 9.3.1 will still be included in this scenario because they are not related to excess heat and therefor not impacted by the altered definition of it.

9.3.3 2030 district heating system scenario

This study will besides looking at the current environmental impact of the DHS in the municipality of Aalborg for 2023, presented in Section 9.3.1 above, then will a future scenario for the DHS in Aalborg municipality also be investigated. The framework and inventory for this scenario will be presented in this Section. This scenario will be based on the baseline, presented in Section 9.3.1, but it will include new heat production units to reflect the future DH production of Aalborg municipality.

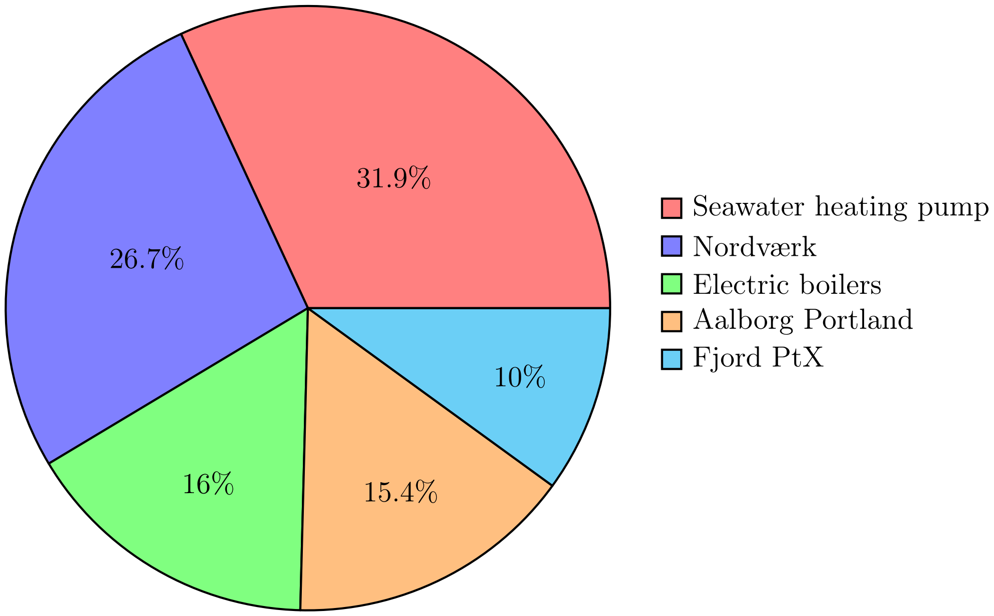

Figure 9.2. Pie chart representing the share of DH from each supplier

This scenario will take place in the year 2030, and it will be largely based on plans, news articles, statements presented in Section 7.3 and an interview with Silas Alvin Hupfeld. An overview of the interview can be found in Appendix A. The year 2030 has been chosen because Aalborg Forsyning has a goal of becoming fossil-free by 2030, and as explained in Section 7.3 then is the plan that Nordjyllandsværket will close in 2028. This will have a big impact on the production of DH in Aalborg municipality since Nordjyllandsværket is responsible for 51,5% of the DH production in Aalborg municipality as of 2023.

As explained in Section 7.3, new heat production units are already planned and being built to replace Nordjyllandsværket. These are primarily a seawater heating pump facility and three electric boilers, excess heat from a PtX facility, and increased excess heat utilisation from a sewage treatment plant. For this future scenario, the heat supply from Aalborg Portland and Nordværk are assumed to stay at the same level as the baseline scenario of the year 2023. For this scenario, the seawater heating pump and the electric boilers will function as the primary heat producers for the DHS.

Seawater heating pump

As stated in the section above then will one of the main heat production units in 20230 be a seawater heating pump with a capacity of 144 MW, and this will be modelled in this section. To model the production of heat from this specific supplier, the following dataset from ecoinvent 3.9.1 has been used: "Heat, air-water heat pump 10kW Europe without Switzerland| heat production, air-water heat pump 10kW | Conseq, U". To make the dataset reflect the chosen case area in this study, the electricity input has been geographically modified. Since this supplier will produce on an industrial scale, then is the electricity input changed from low voltage to medium voltage, since this is assumed to be more representative of industrial heat production, which the seawater heating pump will be. The current input, that is used in the dataset from ecoinvent, is "Electricity, low voltage Europe without Switzerland| market group for electricity, low voltage | Conseq, U". This has been replaced with the following Danish medium voltage electricity market "Electricity, medium voltage DK| market for electricity, medium voltage | Conseq, U". According to DEA [2024] the efficiency of a seawater heat pump is around 400%, why the electricity input is changed from 0,0992 to 0,25. The processes and their values can be seen in Table 9.8 below.

Ecoinvent process	**Original value**	**Modified value**	**Unit**
Heat, air-water heat pump 10kW {Europe without Switzerland}| heat production, air-water heat pump 10kW | Conseq, U	1	1	kg
Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	0.0992	0.25	kWh

Table 9.8. Modified processes for the modelling of the seawater heating pump

Electric boilers

The three electric boilers that Aalborg Forsyning is planning to build are estimated to be responsible for 16% of the DH production in Aalborg municipality [Aalborg Forsyning, 2024b].

The modelling of the three electric boilers will be based on the modelling, that has been done for the electric boiler in the 9.3.1 for the baseline scenario, 9.3.1, where a gas boiler is used but the input of gas in the process is replaced with an input of electricity correspondent to the amount of electricity that is produced from the unit. The choice of modelling the electric boiler like this is based on the arguments from section 9.3.1 which in short terms are: there is no ecoinvent dataset for an electric boiler, and according to the DEA then is the conversion of electricity to thermal energy in an electric boiler almost 100%. Therefore is it deemed reasonable to use the following dataset: "Heat, district or industrial, natural gas Europe without Switzerland| heat production, natural gas, at boiler condensing modulating >100kW |Conseq, U" with the same inputs as presented in Table 9.5.

Power-to-X facility

As mentioned in 7.3, the PtX facility, Fjord PtX, will deliver excess heat from 2028. Since it isn't possible to gather specific data for the Fjordpark PtX facility, the dataset "Hydrogen, liquid RER| chlor-alkali electrolysis, membrane cell | Cut-off, U" from Ecoinvent is used to model the excess heat that is produced at the facility. According to Aalborg Forsyning [2024a], Fjordpark PtX will produce jet fuel by first splitting water into hydrogen in an electrolysis plant, and then converting it into aviation fuel through a synthesis with captured CO_2. The dataset represents the production of hydrogen through a widely utilised commercial process [Energistyrelsen, 2021b]. Consequently, it is deemed appropriate to use for modelling the production of jet fuel at Fjordpark PtX.

There were no suitable consequential datasets available in Ecoinvent for modelling the Fjordpark PtX facility. Consequently, the most appropriate alternative is the dataset previously mentioned. Some inputs of the dataset have been modified to be more representative of the circumstances for the Fjordpark PtX facility.

For the modelling of jet fuel production, the input of electricity and the outputs of power to fuel production Energistyrelsen [2021b] was used. The inputs and outputs of jet fuel production can be seen in Table, 9.9 below.

Input	**Original output (MJ)**
100 MJ electricity	33 Jet fuel
	22 Other hydrocarbons
	25 District heat
	20 Internal use and loss

Table 9.9. Outputs per 100 MJ of electricity input [Energistyrelsen, 2021b]

Because the process in SimaPro uses 1 kg of hydrogen as the output, the numbers in Table 9.9 need to be calculated for the production of 1 kg of hydrogen. The energy content of 1 kg of jet fuel was found to be 43,15 [Division, 2017]. The inputs and outputs from producing 1 kg of hydrogen can be seen in Table 9.10 below.

Input	**Changed output (MJ)**
130,8 MJ	1 kg hydrogen
	28.77 Other hydrocarbons
	32.69 District heat
	26.15 Internal use and loss

Table 9.10. Changed outputs per 1 kg of hydrogen input

Below is an example of an equation for calculating the outputs per one kg of hydrogen, exemplified through electricity consumption. First, it is necessary to determine the amount of MJ used per kg of jet fuel, which can then be multiplied by the values from Table 9.9. The equation for this can be seen below.

$$\frac{43.15 \text{ MJ/kg}}{33 \text{ MJ}} = 1.3 \text{ kg} \tag{9.7}$$

This can then be used as a factor to be multiplied by the other values, which is shown below with an example of electricity.

$$100\,\text{MJ} \times 1.3\,\text{MJ/kg} = 130\,\text{MJ/kg} \tag{9.8}$$

This is then done for all of the outputs in Table 9.10.

These outputs are then used in the dataset "Hydrogen, liquid RER| chlor-alkali electrolysis, membrane cell | Cut-off, U". For the hydrocarbons the following dataset is used "C3 hydrocarbon mixture Europe without Switzerland| C3 hydrocarbon production, mixture, petroleum refinery operation | Conseq, U", this was deemed appropriate to use since the type of hydrocarbon was not specified in Energistyrelsen [2021b]. The output of hydrocarbon in the process in SimaPro is in kg and therefore has to be calculated for the production of one kg of hydrogen. This can be found by dividing the energy usage from Table 9.10 and the energy content for the hydrocarbon, in this case it is C3 or propane, and the energy content is 50,35 MJ/kg [Hydrocarbon engineering, 2020]. The equation can be seen below.

$$\frac{28.77 \text{ MJ}}{50.35 \text{ MJ/kg}} = 0.57 \text{ kg} \tag{9.9}$$

The output of internal use and loss is all assumed to be internal use and is modelled by using the following dataset: "Electricity, medium voltage DK| market for electricity, medium voltage | Conseq, U". The electricity that is used to produce the jet fuel uses the same dataset.

The process used is for the output of 1 kg of hydrogen. However, this does not represent the production of 1 kWh of excess heat. To calculate the amount of hydrogen that needs to be produced to generate 1 kWh of excess heat, values from Table 9.9 are used. As it is determined that when producing 1 kg of hydrogen 32,69 MJ or 9,1 kWh of excess heat is produced, the amount of hydrogen needed to produce 1 kWh of excess heat is found by dividing the amount of hydrogen by the amount of excess heat. This can be seen in the equation below:

$$\frac{1 \text{ kg}}{9.1 \text{ kWh}} = 0.11 \text{ kg/kWh} \tag{9.10}$$

The value, 0,11 kg, is then used to calculate the environmental impacts of producing 1 kWh of excess heat from the production of jet fuel at Fjordpark PtX.

All of the used processes for Fjordpark PtX and the modified values can be seen in Table 9.11 below.

Ecoinvent process	**Original value**	**Modified value**	**Unit**
Hydrogen, liquid {RER}| chlor-alkali electrolysis, membrane cell | Cut-off, U	1	1	kg
C3 hydrocarbon mixture {Europe without Switzerland}| C3 hydrocarbon production, mixture, petroleum refinery operation | Conseq, U	-	0.57	kg
Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	-	26.15	kWh
Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	66.3499664	130.76	MJ

Table 9.11. Modified values for Fjordpark PtX

For the jet fuel produced by Fjordpark PtX, 25% of the environmental impacts will be allocated towards the excess heat. This is based on 25% of the energy that is used at Fjordpark PtX, according to Energistyrelsen [2021b], is converted into DH.

Aalborg Portland and Nordværk

The modelling of the excess heat sources is changed in the 2030 scenario, as the primary heat supplier is changed from the CHP plant to the electric boilers and the seawater heating pump. As a result, 66,6% of the excess heat from Aalborg Portland and Nordværk is modelled as substituting the seawater heating pump, while the remaining 33,4% is modelled as substituting the heat from electric boilers.

9.4 List of inventory processes for all scenarios

Table 9.4 shows the complete inventory of datasets that have been used to model each DH supplier in the three scenarios, baseline, no allocation and future scenario in SimaPro.

Datasets/processes used in the LCI				
Input/output	**Description**	**Ecoinvent process**	**Value**	**Unit**
Output	Output for heat production at Nordjyllandsværket	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, hard coal | Conseq, U	1	MJ
Input	Input of coal in Nordjyllandsværket	Hard coal {Europe, without Russia and Turkey}| market for hard coal | Conseq, U	0,05965	kg
Input	Input of fuel oil in Nordjyllandsværket	Heavy fuel oil {RER}| market group for | Conseq, U	0,00008	kg
Input	Input of gas oil in Nordjyllandsværket	Diesel {RER}| market group for | Conseq, U	0,00002	kg
Input	Input of electricity in Nordjyllandsværket	Electricity, high voltage {DK}| market for electricity, high voltage | Conseq, U	-0,32169	kWh
Output	Output of excess heat from Nordværk	Municipal solid waste {DK}| treatment of municipal solid waste, incineration | Conseq, U	1	kg
Input	Input of electricity production from Nordværk	Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	-0,05437	kWh
Input	Input of heat that is substituted from Nordjyllandsværket	Process modelled by the authors	-0,24107	kWh
Input	Input of heat that is substituted from the electric boiler	Process modelled by the authors	-0,080520 444	kWh
Input	Input of heat that is substituted from the seawater heating pump	Process modelled by the authors	-0,160558 731	kWh
Output	The output of heat from a gas boiler	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating >100kW | Conseq, U	1	MJ
Input	Input of natural gas in the gas boiler	Natural gas, high pressure {DK}| market for natural gas, high pressure | Conseq, U	0,02534	m^3
Input	Input of electricity to the gas boiler	Electricity, low voltage {DK}| market for electricity, low voltage | Conseq, U	0,00108	kWh
Output	The output of heat from an electric boiler	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating >100kW | Conseq, U	1	MJ
Input	Input of electricity for the electric boiler	Electricity, low voltage {DK}| market for electricity, low voltage | Conseq, U	1	MJ

The list continues on the next page.

Output	District heating pipe system in Aalborg municipality	Process modelled by the authors	1	p
Input	Input of steel in the district heating pipes	Chromium steel pipe {GLO}| market for chromium steel pipe | Conseq, U	846	t
Input	Input of high density polyurethane in the district heating pipes	Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | Conseq, U	316	t
Input	Input of high density polyethylene in the district heating pipes	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Conseq, U	483	t
Output	Output of pump station	Pump station {GLO}| market for pump station | Conseq, U	69	p
Output	Output of district heat from seawater heating pump	Process modelled by the authors	1	MJ
Input	Input of heat pump production for the seawater heating pump	Heat, air-water heat pump 10kW Europe without Switzerland| heat production, air-water heat pump 10kW | Conseq, U	1	p
Input	Input of electricity for the seawater heating pump	Electricity, medium voltage DK| market for electricity, medium voltage | Conseq, U	0,25	MJ
Output	Output of heat from Fjordpark PtX	Hydrogen, liquid {RER}| chlor-alkali electrolysis, membrane cell | Cut-off, U	1	kg
Input	Input of hydrocarbon (propane) for Fjordpark PtX	C3 hydrocarbon mixture {Europe without Switzerland}| C3 hydrocarbon production, mixture, petroleum refinery operation | Conseq, U	0,57	kg
Input	Input of electricity for Fjordpark PtX for internal use and loss	Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	26,15	MJ
Input	Input of electricity to produce jet fuel for Fjordpark PtX	Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	130,76	MJ
Input	Input of heat that is substituted from the seawater heating pump	Process modelled by the authors	-21,77113 636	MJ
Input	Input of heat that is substituted from the electric boiler	Process modelled by the authors	-10,91825 758	MJ

Figure 9.3. List of all datasets used in the LCI

Output	Output of excess heat from Aalborg Portland	Cement, Portland {Europe without Switzerland}| cement production, Portland | Conseq, U	1	kg
Input	Input of electricity for Aalborg Portland	Electricity, medium voltage {DK}| market for electricity, medium voltage | Conseq, U	0,0376	kWh
Input	Input of heat that is substituted from Nordjyllandsværket	Process modelled by the authors	-0,493557 052	kWh
Input	Input of heat that is substituted from the seawater heating pump	Process modelled by the authors	-0,328708 996	kWh
Input	Input of heat that is substituted from the electric boilers	Process modelled by the authors	-0,164848 055	kWh

Figure 9.4. List of all datasets used in the LCI

9.5 Environmental impact factors

This section will present all of the environmental impact factors that have been used for each DH supplier in the three scenarios presented in Section 9.3.

Baseline scenario

Table showing all of the environmental impact factors that are used in the baseline scenario with allocation of environmental impacts for excess heat.

Impact category	Unit	Combined heat and power (Nordjyllandsværket)	Waste incinerator (Nordværk)	Aalborg Portland	Natural gas boiler	Electric boiler
Acidification	mol H+ eq	2,40E-03	-2,04E-03	4,06E-04	9,20E-05	8,88E-04
Climate change	kg CO^2 eq	1,11E+00	7,21E-01	2,37E-01	2,24E-01	2,45E-01
Climate change - Biogenic	kg CO^2 eq	-1,53E-04	5,94E+00	2,26E-04	6,47E-06	1,89E-04
Climate change - Fossil	kg CO^2 eq	1,11E+00	-1,53E-09	2,17E-01	2,24E-01	2,44E-01
Climate change - Land use and LU change	kg CO^2 eq	-1,42E-04	8,58E-05	1,99E-02	1,02E-05	1,85E-04
Ecotoxicity, freshwater	CTUe	7,91E-01	-1,73E-04	2,23E+00	3,50E-02	2,45E-01
Particulate matter	disease inc.	-4,98E-09	1,28E+01	8,62E-09	6,03E-10	1,01E-08
Eutrophication, marine	kg N eq	2,92E-04	2,18E-09	2,95E-04	3,81E-05	2,16E-04
Eutrophication, freshwater	kg P eq	2,65E-04	-2,04E-04	-2,62E-06	2,21E-06	2,03E-05
Eutrophication, terrestrial	mol N eq	1,75E-03	-4,14E+00	3,56E-03	4,17E-04	3,28E-03
Human toxicity, cancer	CTUh	-6,90E-11	1,19E-06	2,36E-10	2,76E-11	2,00E-10
Human toxicity, non-cancer	CTUh	5,80E-10	3,94E-09	4,03E-09	1,41E-10	6,09E-09
Ionising radiation	kBq U-235 eq	2,33E-03	1,18E-02	4,45E-03	-1,78E-05	2,43E-04
Land use	Pt	-2,41E+01	-2,43E+01	1,03E+01	9,23E-02	2,13E+01
Ozone depletion	kg CFC11 eq	7,07E-11	7,93E-09	2,43E-09	1,77E-08	1,38E-09
Photochemical ozone formation	kg NMVOC eq	7,54E-04	-9,40E-04	9,50E-04	1,85E-04	6,64E-04
Resource use, fossils	MJ	5,48E+00	-3,59E+00	1,45E-01	3,42E+00	4,71E-01
Resource use, minerals and metals	kg Sb eq	-2,72E-06	-3,36E-08	2,19E-06	-3,09E-08	6,89E-06
Water use	m^3	1,65E-01	1,41E-01	-2,89E-02	2,13E-03	1,17E-02

Figure 9.5. Calculated environmental impact factors for all heat suppliers in the baseline scenario.

No allocation scenario

Table showing all of the environmental impact factors that are used in the baseline scenario with no allocation of environmental impacts for excess heat.

Impact category	Unit	Combined heat and power (Nordjyllandsværket)	Waste incinerator (Nordværk)	Aalborg Portland	Natural gas boiler	Electric boiler
Acidification	mol H+ eq	2,40E-03	0	0	9,20E-05	8,88E-04
Climate change	kg CO^2 eq	1,11E+00	0	0	2,24E-01	2,45E-01
Climate change - Biogenic	kg CO^2 eq	-1,53E-04	0	0	6,47E-06	1,89E-04
Climate change - Fossil	kg CO^2 eq	1,11E+00	0	0	2,24E-01	2,44E-01
Climate change - Land use and LU change	kg CO^2 eq	-1,42E-04	0	0	1,02E-05	1,85E-04
Ecotoxicity, freshwater	CTUe	7,91E-01	0	0	3,50E-02	2,45E-01
Particulate matter	disease inc.	-4,98E-09	0	0	6,03E-10	1,01E-08
Eutrophication, marine	kg N eq	2,92E-04	0	0	3,81E-05	2,16E-04
Eutrophication, freshwater	kg P eq	2,65E-04	0	0	2,21E-06	2,03E-05
Eutrophication, terrestrial	mol N eq	1,75E-03	0	0	4,17E-04	3,28E-03
Human toxicity, cancer	CTUh	-6,90E-11	0	0	2,76E-11	2,00E-10
Human toxicity, non-cancer	CTUh	5,80E-10	0	0	1,41E-10	6,09E-09
Ionising radiation	kBq U-235 eq	2,33E-03	0	0	-1,78E-05	2,43E-04
Land use	Pt	-2,41E+01	0	0	9,23E-02	2,13E+01
Ozone depletion	kg CFC11 eq	7,07E-11	0	0	1,77E-08	1,38E-09
Photochemical ozone formation	kg NMVOC eq	7,54E-04	0	0	1,85E-04	6,64E-04
Resource use, fossils	MJ	5,48E+00	0	0	3,42E+00	4,71E-01
Resource use, minerals and metals	kg Sb eq	-2,72E-06	0	0	-3,09E-08	6,89E-06
Water use	m^3	1,65E-01	0	0	2,13E-03	1,17E-02

Figure 9.6. Calculated environmental impact factors for all heat suppliers in the baseline scenario with no allocation of environmental impacts to excess heat suppliers.

2030 district heating scenario

Table showing all of the environmental impact factors that are used in the future scenario.

Impact category	Unit	Seawater heating pump	Waste incinerator (Nordværk)	Aalborg Portland	Fjordpark PtX	Electric boiler
Acidification	mol H+ eq	2,35E-04	-4,62E-04	1,12E-03	1,30E-03	8,88E-04
Climate change	kg CO^2 eq	4,00E-02	1,51E+00	5,93E-01	9,32E-02	2,45E-01
Climate change - Biogenic	kg CO^2 eq	4,48E-05	-8,82E-05	1,44E-04	4,86E-04	1,89E-04
Climate change - Fossil	kg CO^2 eq	4,00E-02	1,51E+00	5,73E-01	9,25E-02	2,44E-01
Climate change - Land use and LU change	kg CO^2 eq	4,24E-05	3,82E-04	1,98E-02	2,83E-04	1,85E-04
Ecotoxicity, freshwater	CTUe	6,55E-02	6,70E+00	2,47E+00	1,45E+00	2,45E-01
Particulate matter	disease inc.	2,42E-09	-8,75E-09	5,36E-09	1,24E-08	1,01E-08
Eutrophication, marine	kg N eq	5,03E-05	2,45E-04	3,67E-04	2,51E-04	2,16E-04
Eutrophication, freshwater	kg P eq	6,37E-06	2,78E-05	8,81E-05	6,77E-05	2,03E-05
Eutrophication, terrestrial	mol N eq	7,76E-04	9,78E-04	3,70E-03	3,21E-03	3,28E-03
Human toxicity, cancer	CTUh	5,24E-11	4,88E-10	1,80E-10	2,20E-10	2,00E-10
Human toxicity, non-cancer	CTUh	1,77E-09	8,82E-09	3,19E-09	5,62E-09	6,09E-09
Ionising radiation	kBq U-235 eq	7,36E-07	-4,22E-03	5,25E-03	1,14E-02	2,43E-04
Land use	Pt	5,09E+00	-1,30E+01	-1,33E+00	1,42E+01	2,13E+01
Ozone depletion	kg CFC11 eq	2,53E-08	-1,13E-08	-3,68E-09	2,80E-07	1,38E-09
Photochemical ozone formation	kg NMVOC eq	1,62E-04	1,68E-04	1,12E-03	6,61E-04	6,64E-04
Resource use, fossils	MJ	1,46E-01	-3,81E-03	2,01E+00	6,59E-01	4,71E-01
Resource use, minerals and metals	kg Sb eq	2,57E-06	-3,94E-06	-1,34E-07	5,22E-06	6,89E-06
Water use	m^3	3,69E-03	2,05E-01	2,75E-02	3,12E-01	1,17E-02

Figure 9.7. Calculated environmental impact factors for all heat suppliers in the 2030 scenario.

Life Cycle Assessment results 10

This chapter looks at the results of the LCA of the DH scenarios described in Chapter 9. This is done to analyse the environmental impact of the DHS in Aalborg municipality, and the impact of using excess heat on these results.

Impact assessment results per kWh	Unit	Baseline	Baseline without excess heat impact	2030 scenario	2030 without excess heat impact
Acidification	mol H+ eq	7,99E-04	1,28E-03	4,16E-04	2,37E-04
Climate change	kg CO^2 eq	8,18E-01	5,90E-01	5,60E-01	5,65E-02
Climate change - bio	kg CO^2 eq	1,58E+00	-7,06E-05	9,59E-05	4,86E-05
Climate change - Fossil	kg CO^2 eq	6,23E-01	5,90E-01	5,56E-01	5,64E-02
Climate change - luluc	kg CO^2 eq	3,02E-03	-6,44E-05	3,23E-03	4,76E-05
Ecotoxicity, freshwater	CTUe	7,84E-01	4,41E-01	2,40E+00	8,67E-02
Particulate matter	disease inc.	3,40E+00	-2,10E-09	2,34E-09	2,61E-09
Eutrophication, marine	kg N eq	2,07E-04	1,61E-04	2,02E-04	5,54E-05
Eutrophication, freshwater	kg P eq	8,50E-05	1,40E-04	3,57E-05	7,96E-06
Eutrophication, terrestrial	mol N eq	-1,10E+00	1,03E-03	1,97E-03	8,15E-04
Human toxicity, cancer	CTUh	3,17E-07	-3,91E-12	2,55E-10	7,49E-11
Human toxicity, non-cancer	CTUh	2,16E-09	4,94E-10	5,01E-09	2,57E-11
Ionising radiation	kBq U-235 eq	5,00E-03	1,17E-03	8,25E-04	4,92E-11
Land use	Pt	-1,68E+01	-1,19E+01	2,82E+00	1,60E-09
Ozone depletion	kg CFC11 eq	3,48E-09	9,88E-10	3,28E-08	1,51E-09
Photochemical ozone formation	kg NMVOC eq	3,25E-04	4,29E-04	4,60E-04	5,08E+00
Resource use, fossils	MJ	2,12E+00	3,05E+00	5,68E-01	8,46E-09
Resource use, minerals and metals	kg Sb eq	-9,00E-07	-1,23E-06	1,40E-06	1,77E-04
Water use	m^3	1,21E-01	8,74E-02	9,54E-02	5,23E-03

Table 10.1. Impact assessment results for the studied scenarios per kWh

Table 10.1 above shows all of the results for all impact categories for all four scenarios that are investigated in this study. The results have been colour-coded so that low impact values are green, moderate impacts are orange to yellow and red indicates the highest impact values. The results seen in the table will be referred to, throughout the following chapter.

10.1 Baseline scenario

This section presents the results of the baseline scenario that is described in Section 9.3.1.

In Table 10.1 the impact assessment results of the baseline scenario can be seen. It shows that the baseline scenario has the largest overall environmental impact, with 8 of the 19 impact categories having the highest value in this scenario. These are impacts such as *Climate change*, *Particulate matter* and *water use*.

When looking at the environmental impact of producing 1 kWh of heat, it can be seen that the DHS, on average, produces 0,8 kg CO_2-eq. In total this results in 1.457.191 tonnes of CO_2-eq. in 2023. Compared to Aalborg Forsyning's reported numbers of 0,12 kg of CO_2-emissions per kWh and a total of 230.370 tonnes of CO_2, the results are 6,3 times higher [Aalborg Forsyning, 2023a]. Without knowing the exact method Aalborg Forsyning has used to calculate the emissions it can be difficult to pinpoint the exact reasons for this difference. However, the main difference could be due to the use of consequential datasets when modelling the DHS. When modelling Nordjyllandsværket, the main heat supplier, with an attributional dataset, the total CO_2-emissions become 625.520 tonnes, showing a large decrease from just one change. As such, the results of this baseline should not and are not intended to, be used for comparison with current estimations for the environmental impact of the DHS in Aalborg. As the consequential datasets consider a much wider scope of impacts from the processes as well as the wider consequences, the results between the attributional and consequential datasets vary widely. Another example of this is the consequential dataset used to model waste incineration resulting in negative values e.g. *Acidification*, *Eutrophication, freshwater and terrestrial*, *Land use* and *Resource use*, while the corresponding attributional dataset shows positive values for these impact categories. While the results are not comparable to Aalborg Forsyning's reported numbers, it does show how LCA and especially the consequential method, can contribute to different results and understandings of a system.

Although many of the impact categories show the highest values in the baseline scenario, some categories such as *Land use*, *Eutrophication, terrestrial* and *Photochemical ozone formation* show the lowest value in the baseline scenario compared to all other scenarios.

10.1.1 Comparing allocation methods

While in this study the excess heat is allocated a certain amount of the environmental impacts occurring during its production, the current common approach is to view excess heat as having no impact, as described in Section 1.1. In Table 10.1 the results of the baseline scenario, when no impact is allocated to EH can be seen in the second column. This shows that a majority of the impact category results decrease when there is no impact from excess heat, while a few category results increase. The difference in percentages can be seen in Figure 10.1. This figure shows the difference in results when no impact is allocated to the excess heat. Here it can be seen that a majority of the impact categories see a decrease in results. This is the case e.g. *climate change*, which sees a decrease of 28% or 407.415 tonnes CO_2-eqs. However, for the impact categories *acidification*, *eutrophication, freshwater*, *eutrophication, terrestrial*, *land use* and *resource use, fossils* an increase can be seen compared to the results allocating environmental impacts to the excess heat.

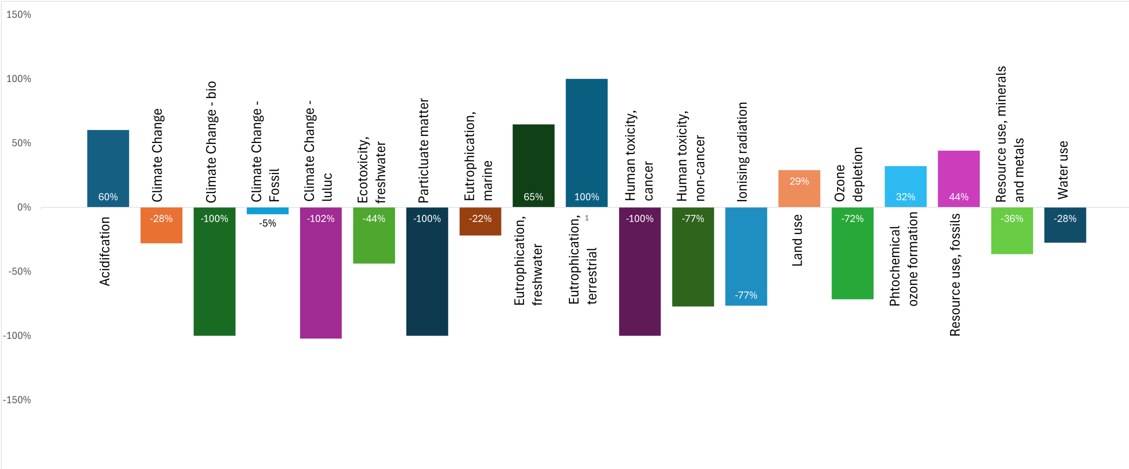

Figure 10.1. Comparison of results from the model with no impact from excess heat to baseline scenario

One explanation for this can be found in the consequential LCA approach. Using the consequential approach, the excess heat production is modelled as substituting the heat production from the coal-fired CHP plant, Nordjyllandsværket. As mentioned previously, this approach results in some of the impact category results from the excess heat production having negative values. Therefore, the inclusion of environmental impacts from excess heat leads to a lower environmental impact in some categories. This could serve as an incentive to include the environmental impacts of excess heat when assessing DHSs. Furthermore, it shows that environmental assessments should not only be limited to climate change and CO_2-eqs. as CO_2-emissions are not representative of an impact across the broad spectrum of impact categories.

This comparison also shows that the method or approach to allocating environmental impact to excess heat has a large impact on the results. The common argument for not allocating impact to the excess heat is that it would be produced and wasted regardless of its use in the DHS. However, this approach can be misleading, especially if there is a desire to base a large part of the heat supply on excess heat. In a hypothetical scenario where the entire DHS is based on excess heat from fossil-fuel-fired industries, the DHS could still be classified as fossil- and emissions-free, if no impacts are allocated to the excess heat. This is despite the source of the heat being fossil-based. While using excess heat to replace the primary production of heat does contribute to lowering environmental impacts, it should not be seen as a sustainable solution without considering the environmental impact of the excess heat sources. The view of excess heat being impact-free also raises an issue in terms of all excess heat sources being viewed as equals. With no impact allocated to the excess heat suppliers, there is no difference in the heat being sourced from a fossil-fuelled source or a renewable energy-fuelled source. This lack of consideration of the impacts of the excess heat sources can lead to decisions and plans made on an insufficient basis.

10.2 2030 scenario

A comparison of the 2030 scenario and the baseline scenario can be seen in 10.2. Compared to the baseline scenario it can be seen that by replacing the coal-fired CHP plant with other alternatives, the impact is decreased across 11 of the 19 categories.

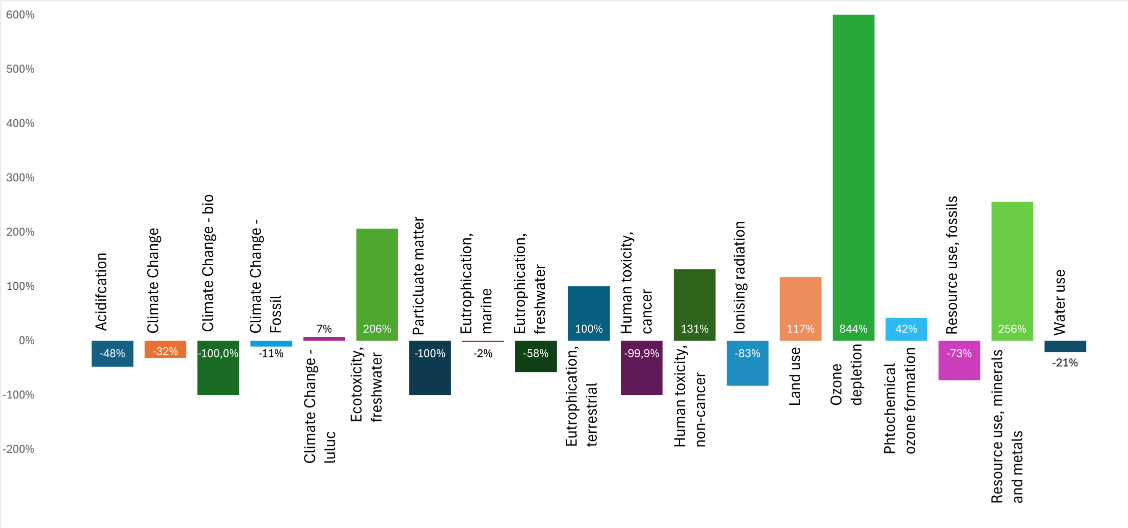

Figure 10.2. Difference between results from the 2030 scenario and baseline

Impact categories such as *Acidification, Climate change, Climate change - bio, Particulate matter* and *Fossil resource use* show significant decreases in this scenario, while *Freshwater ecotoxicity, non-cancerous human toxicity, Land use, Ozone depletion* and *Mineral and metal resource use* show large increases compared to the baseline scenario. The seawater heating pumps, electric boilers and the excess heat from PtX processes used to replace the heat from the coal-fired CHP plant are all fuelled by electricity. As this electricity is assumed to be based on renewable energy sources, it is natural that a majority of the impact categories show a decrease. The categories showing an increase in results can likely be attributed to the impacts of infrastructure needed for renewable energy sources.

In Figure 10.3 the difference between the 2030 scenario with and without impacts from excess heat can be seen.

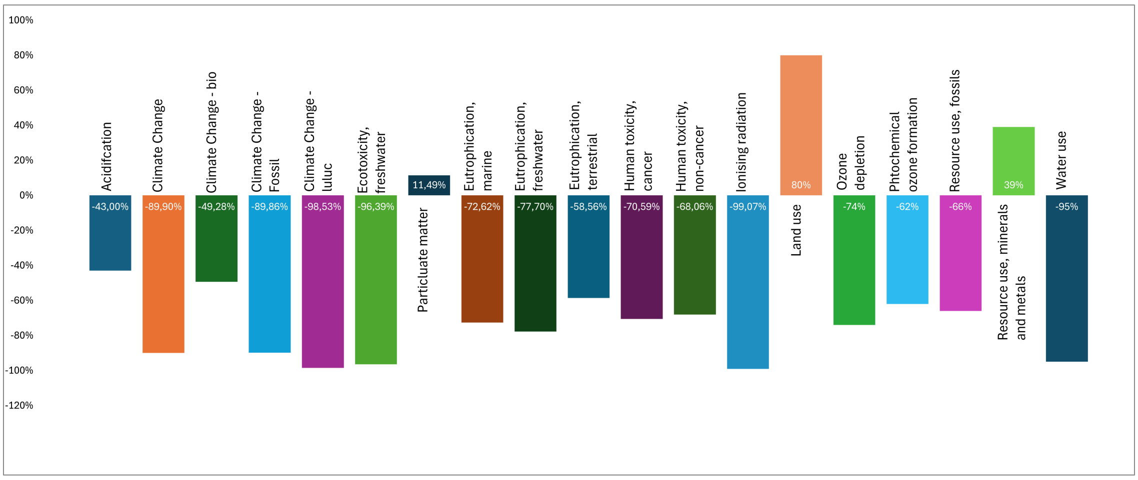

Figure 10.3. Impact on future scenario results when no impact from excess heat

The figure shows that all impact categories except three show a decrease in impact of at least 48% with a majority showing a decrease closer to 100%. *Particulate matter, land* *use* and *Resource use, minerals and metals* are the three categories that show an increase, which can be attributed to the consequential modelling of the excess heat resulting in a substitution of heat produced by the seawater heating pumps and the electric boilers. As the primary heat production is reliant on renewable energy such as solar and wind power, it has a relatively large impact on the *Land use* and *Resource use, minerals and metals* impact categories due to the nature of these technologies. Therefore, as the excess heat substitutes the primary heat production, these impacts decrease, and as a result, these impact categories see an increase when no impact is allocated to the excess heat. On average, the results decrease by 57% in the 2030 scenario when not allocating environmental impact to the excess heat, while for the baseline scenario, the results decrease by 24% when no impact of excess heat is included. While the additional excess heat in the 2030 scenario from the PtX facility does play some part in this increased difference, the main contributor is the new primary heat supply. As the excess heat is now substituting the heat from renewable energy-fuelled sources rather than a fossil-fuelled source, the benefit of utilising the excess heat diminishes. In other words, the environmental impact of excess heat increases as the environmental impact of the main heat supply decreases.

This is another argument for why looking at the environmental impact of excess heat can be useful. When using a consequential approach, and allocating environmental impact to excess heat, the choice of using excess heat from high-impact sources becomes less beneficial the less impactful the primary heat supply is. As a result, decision-makers using results based on this approach might rethink the validity of incorporating fossil-fuel-based excess heat into the DHS, when the primary heat supply has a lower impact.

10.2.1 LCA results on a time basis

As the LCA has been calculated on an hourly basis, it is possible to see how the environmental impact fluctuates throughout the year. As the temperature fluctuates throughout the year, the heat supply similarly changes with less heat supplied during warmer periods. This results in the environmental impact following a similar trend, with lower impacts when the heat supply is lower. Therefore, it is interesting to see how the environmental impact of producing 1 kWh of heat varies throughout the year. This can be seen in Figure 10.4.

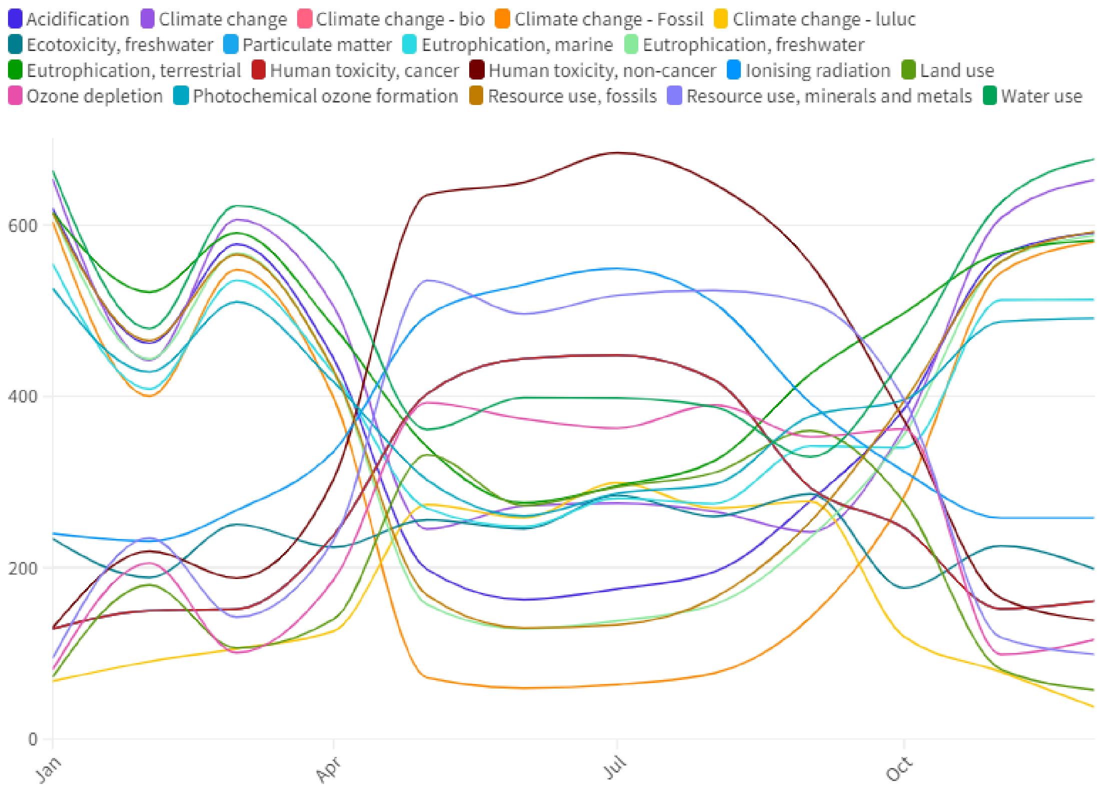

Figure 10.4. Environmental impacts of producing 1 kWh of heat throughout 2023

As the environmental impact results are in different units, and as the values of the results vary widely, the data has been indexed to create a better visualisation. While the impact categories are difficult to distinguish from each other in Figure 10.4 above, a general pattern can be identified. Some impact category results have higher values at the beginning and end of the year, with lower values during the middle of the year, while other categories follow an opposite pattern. The individual graphs for each impact category can be seen in figure 10.5, showing the pattern more clearly.

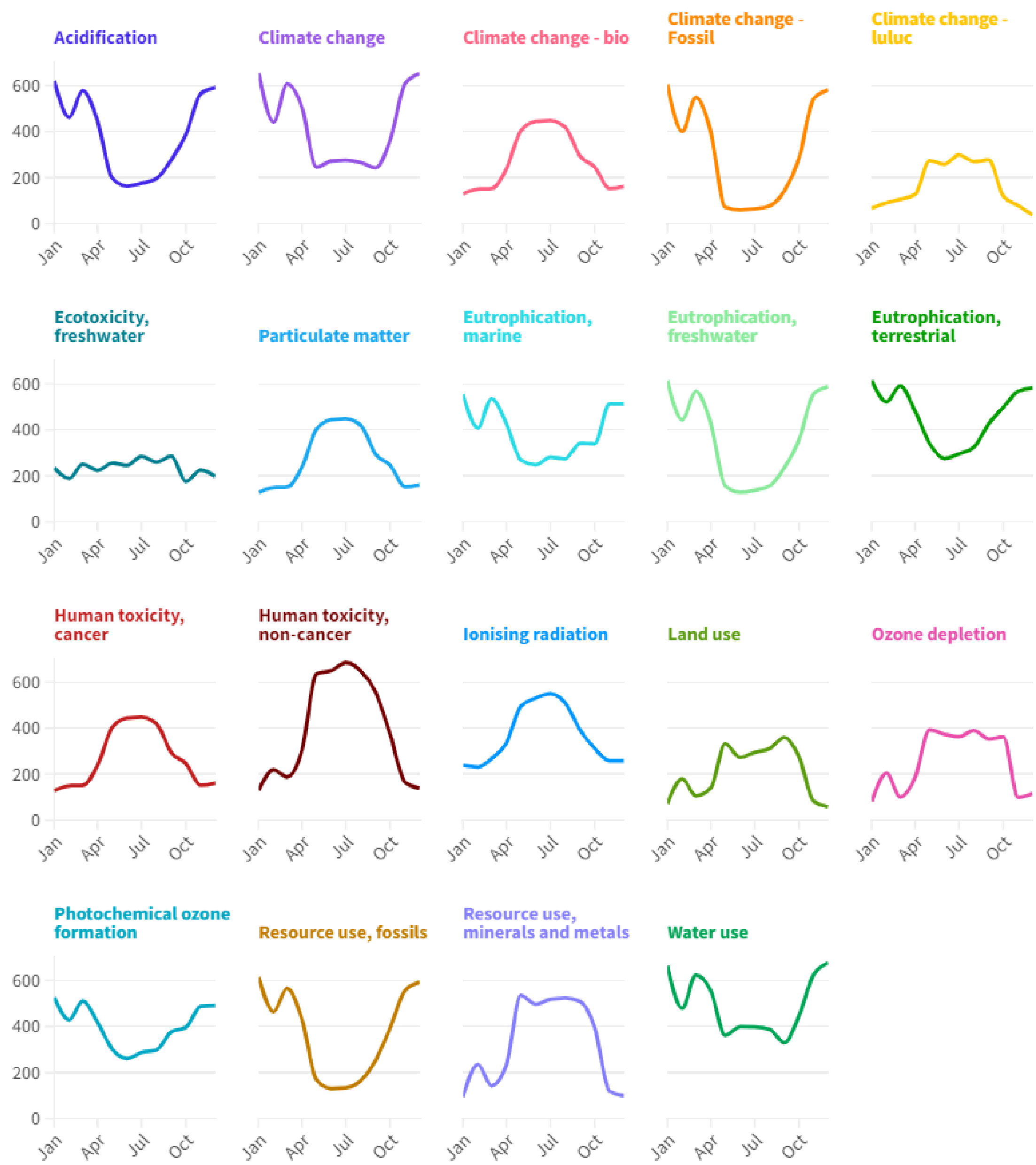

Figure 10.5. Individual line charts showing the environmental impacts of producing 1 kWh of heat throughout 2023

One possible explanation for this can be seen when looking at how the composition of the heat supply changes throughout the year. This can be seen in figure 10.6.

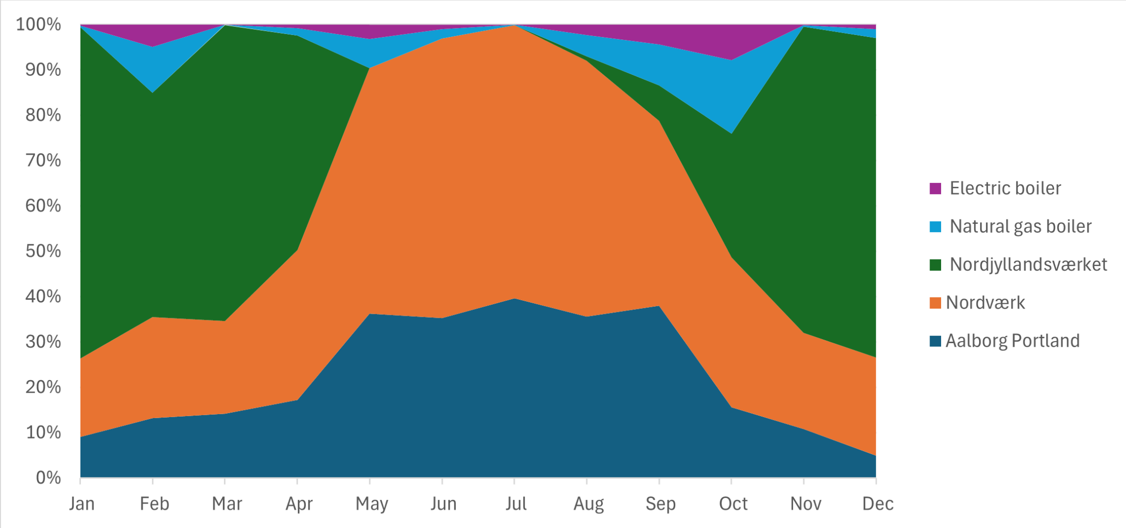

Figure 10.6. Share of heat supply throughout 2023

Figure 10.6 shows that during the colder months (January-April and October-December), Nordjyllandsværket is responsible for the vast majority of the heat supply, while in the warmer months (May-September) Nordværk and Aalborg Portland completely replace the heat supplied by Nordjyllandsværket. When comparing the graphs in figure 10.6 and 10.4 it becomes clear that the two are correlated. Certain environmental impacts associated with Nordjyllandsværket peak at the same time as the heat supply peaks for this heat source, while they are at their lowest when Nordjyllandsværket is not supplying heat. In figure 10.7 this can be seen, using the examples of the impact categories *Climate Change* and *Ressource use, minerals and metals*

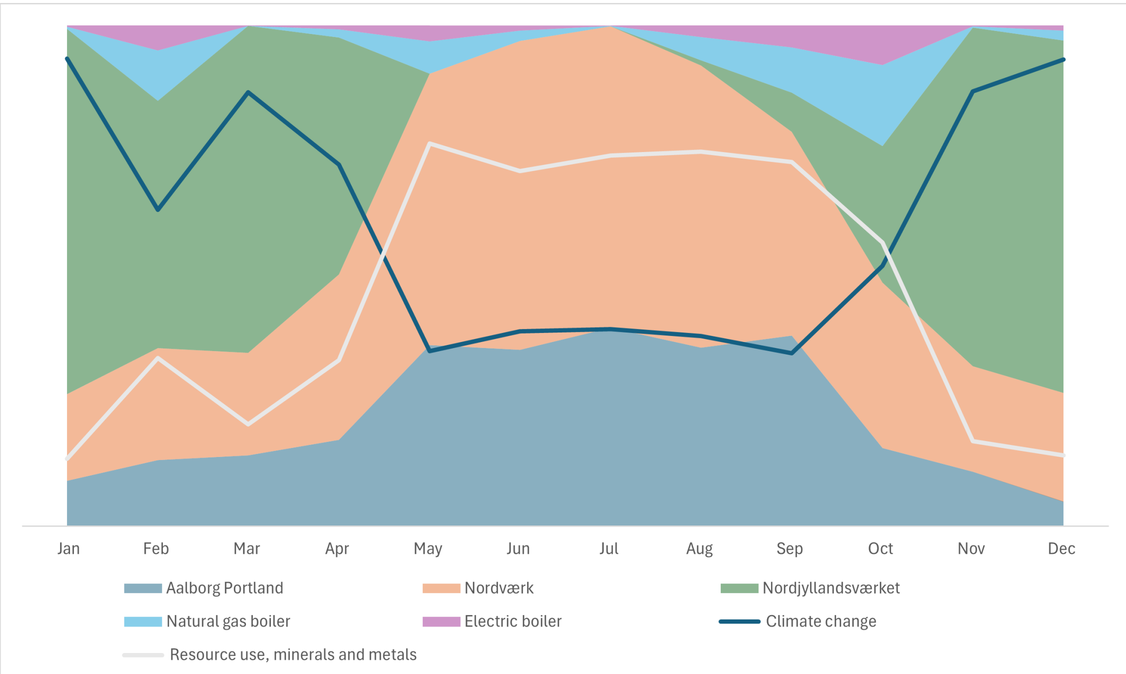

Figure 10.7. Graph showing the relation between the heat supply and the environmental impact

Figure 10.7 clearly shows the relation between the heat supply and the impact category results, as well as the inverse relation of some categories such as the ones depicted in the graph. While the *Climate Change*-impact category decreases as Nordværk and Aalborg Portland gradually replace Nordjyllandsværket as the main heat suppliers, the impact category *Resource use, minerals and metals* increases. Compared to the more traditional approach of calculating and presenting the total LCA results of a product or system, this dynamic approach helps contextualise the results, which can lead to new conclusions that would not otherwise be apparent. These results show that when analysing a dynamic system such as a DHS, static LCA results do not show the whole picture. Several possible conclusions can be made based on the graph above, such as the fact that the *Climate Change*-impact category or CO_2-emissions do not indicate whether there is an increase or decrease in the system's total environmental impact. This is an interesting conclusion, as it can be seen from the literature review in Chapter 2 that the current dominating approach is to only focus on CO_2-emissions when analysing the environmental impact of excess heat and DHSs. This can lead to decision-making that prioritises lowering CO_2-emissions without considering whether it is the best overall solution in terms of the environment and sustainability. It can also be used to help better plan the heat supply. While the current approach of basing the heat supply in the warmer months on Aalborg Portland and Nordværk leads to lower CO_2-emissions, other impacts are increasing, even surpassing the coal-fired CHP-plant. This could suggest that the chosen heat suppliers in the low-demand periods are not the best possible solution and indicate a need to explore alternative and less impactful heat sources.

While the above graphs show the aggregated monthly results, the daily aggregated results show an even clearer picture of the inverse relationship between the two impact categories. This can be seen in Figure 10.8 below.

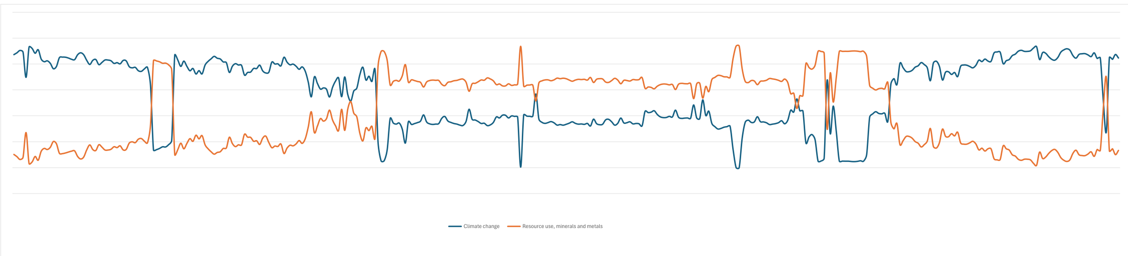

Figure 10.8. The aggregated daily impact results of the impact categories *Climate Change* and *Resource use, minerals and metals*

Furthermore, an even more detailed view is provided by the hourly aggregated results, highlighting the fluctuations and inverse relationship on an hourly basis. This is illustrated in Figure 10.9 below.

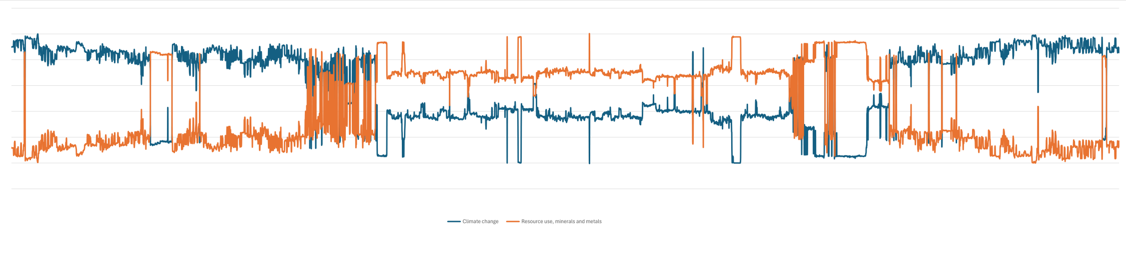

Figure 10.9. The aggregated hourly impact results of the impact categories *Climate Change* and *Resource use, minerals and metals*

Besides better showing the inverse relationship between the two impact categories, then offers an hourly or daily LCA model several advantages over traditional LCA.

It is ideal to provide a temporal overview of the life cycle of a process or product where materials or suppliers are changing daily, which is the case with the DHS of Aalborg municipality. It is also better to show fluctuations in the heat demand and supply and how this affects the environmental impact of the system.

An hourly model also enables precise emission profiling by tracking variations in emissions throughout the day. This is relevant to know because emissions can fluctuate based on different factors such as heat demand, energy supply, and operational changes (for example if one heat producer is shut down for maintenance). By reflecting the environmental impacts as close to real-time operations as possible it becomes easier to identify which supplier has the biggest impact on the DHS. Thereby it also provides a more accurate picture of the environmental impact of the DHS at any given time.

Doing an hourly LCA model helps to connect and align the goals and perspectives of environmental planning with energy planning by providing both a detailed and dynamic understanding of heat production and consumption patterns and their relative environmental impacts. It also helps to see how actual real-time operations affect the environmental impact of the system. This level of detail ensures that both environmental and energy strategies are developed with a better understanding of their interdependencies and impacts.

As mentioned in the sections above, an hourly LCA model can help identify peaks. This Section will therefore look into some of the peaks that are in the model as presented in Figure 10.8 and 10.9.

The identified peaks that will be investigated in this section are the following day(s): February 16th - 22nd, June 17th and September 30th - October 9th.

For the peak from February 16th to 22nd, the hourly data shows that Nordjyllandsværket did not supply any heat. Therefore the natural gas boiler and electric boiler took over the heat production during this period. After February 22nd, Nordjyllandsværket gradually resumed heat supply, leading to a reduction in the heat provided by the two boilers. The reason for Nordjyllandsværket's downtime during this period is not known, but it is likely the cause of the observed peak.

A similar situation occurred on June 17th, where Nordjyllandsværket supplied only 1% of heat during the early hours and then entirely halted supply for most of the day. The heat supply was up and running again on June 18th. As with the previous peak, the reason for this downtime at Nordjyllandsværket is not known. As with the peak from February 16th to 22nd, the natural gas boiler and electric boiler took over the majority of the heat production during this period.

The peak September 30th - October 9th also seems to be a result of a longer downtime of Nordjyllandsværket. Also here the natural gas boiler and the electric boiler replaced

Nordjyllandsværket has a relatively high impact on *climate change* but a low impact on *resource use, minerals, and metals*. Conversely, the natural gas boiler and electric boiler have lower *climate change* impacts and higher impacts on *resource use, minerals, and metals*. This implies, that when Nordjyllandsværket is offline, the contributions to the impact categories of *climate change* and *resource use, minerals, and metals* invert. This inverse relationship is confirmed by the peaks during Nordjyllandsværket's downtime, which also underscores its role in the overall environmental impact of the DHS of Aalborg municipality.

10.3 Limitations

This section outlines the limitations encountered during the LCA study. Understanding and presenting these constraints helps to be more transparent regarding the limitations of this LCA study and its modelling.

10.3.1 Data availability

The LCA model is understood to have some possibilities for more detail which were not deemed most crucial for the question posed in this study in terms of supporting real-world decision-making. Therefore some assumptions might not represent the real-world case as close as they could be. These are specifically the primary heat-producing processes from Nordværk and Aalborg Portland as those supply the heat as a secondary product. Due to concerns of disclosing information that could be disadvantageous for them in regard to competition with rivalling companies in the markets for their primary products, it is hard to acquire detailed information concerning the exact composition of the fuel, energy density of the fuel, amounts burned at every hour, places of procurement and other details which would align the model more with the reality. Another option to further the knowledge on resembling the reality better could also be the increased use of direct contact with people from the companies using their knowledge more to incorporate and reflect more accuracy in the model. The efforts for getting access to the stated information did not seem necessary or even counterproductive as for some data an NDA might have been needed which would prevent the study from actually being able to add to a public and academic discussion that should gain from the findings of the research. The current results resemble reality to a sufficient extent to address issues in the assessment of environmental impacts and the allocation of burdens stemming from excess heat. Datasets for processes were generally used from ecoinvent. The exact processes of the suppliers are not modelled. Yet the generic processes in ecoinvent were altered in cases where there seemed to be more reasonable information available or actual information from sources stated in the 9.4. This approach could be improved the more actual information from the case were available.

10.3.2 Time frame

The modelled impacts are based on the actual demand and supply from only one year. The information on that year is directly provided by the DHS operator Aalborg Forsyning. By that, the baseline of the last full year since the research was conducted can be used as a point of departure for discussing future changes in scenarios and how the environmental impacts are assessed. The foundation could be improved upon by using several years of data. Yet due to the recent years before 2023 being somewhat atypical in terms of supply and demand stemming from unusual circumstances coming from a global pandemic and an energy crisis since 2020, this was not done. Further, then the process of acquiring the necessary data was complicated and took longer than expected due to legal uncertainty in the internal processes at the distributor regarding the accessibility of the data. When the issue was resolved another request would have had to be issued for more information on other years which would have started the process anew which was too late in the process of this study.

10.3.3 Consequential vs. attributional modelling

While a choice has been made to use a consequential approach due to the reasons stated in Section 6.2, a few limitations and drawbacks can be mentioned. As consequential modelling includes a broader scope of impacts and interactions between processes, it also increases the complexity compared to an attributional approach. This complexity can lead to increased uncertainty, both in the data sources and the modelling choices. As a result, while the consequential approach leads to a more comprehensive and realistic result, it also leads to more uncertainty and sources of error compared to the more simple attributional modelling.

10.3.4 Modelling choices

When conducting an LCA, there are many choices and decisions made that can impact the results. Many of these decisions are not always apparent or guided by certain standards and guidelines, and depending on circumstances and the individual LCA practitioner different choices can be made. As such the results of this study are not suitable for direct comparison with other studies, however, the study has been described with a goal of transparency in mind. This transparency gives insights into the decisions made, and the calculations that have been done and thereby leaves room for criticism, comparison and improvement in other future studies regarding the same subject of the environmental impact of excess heat in DHSs.

Discussion of excess heat 11

The following discussion looks further into the findings of this study on the environmental impact of utilising excess heat in the DHS of Aalborg municipality. This is done by examining the allocation of emissions, the roles of various stakeholders, and the inclusion of temporal aspects in the LCA model. The discussion aims to explore the implications of these findings for policy, industry practices, and future research directions, highlighting both the challenges and opportunities in optimising the use of excess heat for environmental benefits.

11.1 Discussion of LCA results

In Chapter 10 the results and outcome of using a consequential and time-based LCA model when looking at the environmental impact of using excess heat can be seen. It shows the environmental impact of a DHS when different definitions of excess heat are used, as well as how this impact changes when the primary heat supply changes. Furthermore, it is shown how an LCA model using hourly data, can be used to gain more detailed insights into the factors influencing the results. However, what is not made clear are the potential use cases for this approach and the results it shows.

By using a consequential LCA approach to study the environmental impacts of a DHS, it is first and foremost possible to gain insight into the impacts that are not considered when using the common approach of only calculating GHG emissions, as shown in the literature review in Chapter 2. The importance of considering a broader spectrum of environmental impacts is also shown in the results, as certain impacts are shown to have an inverse relationship with the *climate change* impact category. With low values for the *climate change* impact category corresponding with higher values for other impact categories such as *Resource use, minerals and metals* throughout the year, it is clear that climate change or GHG emissions can not be the only aspect considered if the system is to be considered sustainable. Therefore, it can be argued that in order to create and plan a more sustainable DHS, it is necessary to study a broad scope of environmental impacts, as solutions that reduce GHG emissions are not necessarily good for the environment. This approach gives decision-makers a better foundation to base their decisions on, which might lead to, research into and utilisation of, new solutions. These new solutions could be new untapped excess heat sources as well as new primary heat sources. This approach for evaluating the environmental consequences of DHS and excess heat can also serve to manage industrial shutdowns, minimising mismatches between supply, demand, and environmental impacts. Additionally, it can help in the planning process of expanding

DHSs to prevent supplying heat during periods of high environmental impacts.

In connection with this, it is relevant to discuss the potential target audience for this approach and its results. The main focus of this study has been the DH owners, Aalborg Forsyning, as they are directly in charge of decisions related to the DHS. However, it would also be relevant for policymakers at a national and European level, as these results could help influence the perception of how environmentally impactful the DHSs are. Using this approach, current DHSs may show a bigger environmental impact than what was initially perceived, which could lead to an increased focus on lowering these impacts through new policies and initiatives. It could also lead to Excess heat suppliers looking more critically at their operations if there is an increased focus on their external impacts.

Although the approach used in this study can be used to support decision-making in terms of the environmental impact, it is lacking aspects such as economic and social factors. Without these elements, it is difficult to identify the best possible solutions, and why these aspects could be beneficial to incorporate in future studies.

11.2 Time dimension in Life Cycle Assessment

In this study, an important aspect is the inclusion of a temporal dimension in the LCA modelling, which was also identified as a knowledge gap in the literature in Section 2.5. Specifically, the analysis employs hourly heat supply data to calculate the corresponding hourly environmental impact. This granular approach offers both advantages and drawbacks. One advantage of utilising hourly data is the ability to capture nuanced fluctuations in the environmental impact over time. By dissecting the data into hourly intervals, it is possible to see changes occurring from hour to hour. This detailed analysis provides insights into temporal dynamics that can increase the understanding of a system's behaviour, as demonstrated in Section 10.2.1. However, the granularity of hourly data also presents challenges. Graphs and charts generated from hourly data may show irregular patterns that can be visually messy and challenging to interpret. Conversely, aggregation at daily or monthly levels results in smoother and more visually appealing representations. This has been done in this study to improve visualisations. Yet, this simplification sacrifices the detailed insights gained from analysing individual hours. Moreover, working with hourly data requires handling significantly larger datasets compared to daily or monthly datasets. With 8760 data points for each year, managing and processing such extensive datasets can be cumbersome and resource-intensive, potentially complicating the analysis process. Therefore the level of detail, in this case hourly, also poses a challenge. Additionally, it could also lead to an increase in errors during data processing due to its size and complexity. The choice of temporal granularity when conducting an LCA should be a balance between detail and manageability. While hourly data offers more detailed insights, one should weigh its benefits against the increased complexity it entails. Ultimately, the level of detail selected should align with the specific objectives and requirements of the study, ensuring that the chosen approach effectively serves the research goals.

This study has explored a potential methodological approach to incorporate the temporal aspect into an LCA. By doing so, the study has contributed to addressing and "filling" the knowledge gap identified in Section 2.5. This contribution can help to enhance the understanding of how temporal factors can be systematically integrated into LCA methodologies, providing a more comprehensive framework for assessing environmental impacts over time.

11.3 Different definitions and their impact on allocation method

As the literature review concluded, some articles specifically define excess heat, while others do not. These definitions vary based on factors such as temperature, origin, stability, and quality of the heat. Articles like Wahlroos et al. [2018] define waste heat by temperature and the stability of supply, while others like Sacchi and Ramsheva [2017] distinguish between true and false excess heat. Regulatory definitions by the Danish national regulator define excess heat as unavoidable heat produced as a byproduct from various sectors that would otherwise be lost without access to a DHS as presented in Section 1.1.

When looking at true excess heat, is defined to be an unavoidable byproduct of processes, with no additional fuels used purposely to produce it. Contrary to the false excess heat that results from processes where additional fuels are purposely used to produce it, it is a less genuine form of waste heat. True excess heat is often seen as a "*free*" resource or carbon-neutral and impact-neutral because it doesn't require additional fuel consumption. To completely rule out the occurrence of false excess heat an internal perspective on the excess heat suppliers would be necessary to understand their production decisions. These are not disclosed, so false excess heat being supplied to the DHS can not be completely ruled out False excess heat is considered less environmentally beneficial since it involves intentional energy input, contradicting the principle of utilising unavoidable byproducts. These perspectives stand to be challenged to some extent here as in LCAs, true excess heat often gets zero emissions allocated to it, implying it doesn't contribute additional environmental burdens. This perspective was not only subject to be questioned in the literature review but has also been further supported by the conducted LCA in this study to be a dangerous assumption if blindly relied on. This is argued for because the excess heat impacts are not being properly accounted for by all beneficiaries entailing the possibility of letting the impacts fall under the table whilst reporting reductions on all sides. Here it could be argued that clear rules for how and who has to take responsibility for the impacts and reports on them. Implications on the background of various national and EU regulations could be that the current practice is not optimal to genuinely report the development in environmental impacts, be it positive or negative.

In the observed case, Aalborg Forsyning has the goal of being fossil-free by 2030 [Aalborg Kommune, 2022]. However, this goal may be compromised depending on which definition is used and how burdens are allocated issue. If Aalborg Forsyning claims fossil fuel reductions due to the use of excess heat, it must be ensured that the same reductions are not simultaneously claimed by the suppliers. This requires a clear definition and agreement on burden allocation to maintain the integrity of the "fossil-free" claim. The situation of the case and the stated technical definitions leave space for interpretations on how the impact of excess heat is accounted for and by whom. This question of responsibility is to be discussed and done in the following.

11.4 Allocating responsibility

This study focuses on identifying the environmental impacts of utilising excess heat in the DHS of Aalborg municipality by conducting an LCA of it. The results from this LCA are presented in 10, but these only focus on the impacts themselves, and don't give a clear answer regarding who should be responsible for the environmental impact. Aalborg Forsyning, the operator of the DHS, sources excess heat from industrial facilities like Aalborg Portland and Nordværk. The challenge arises in deciding whether the environmental impacts should be attributed to the companies producing the excess heat or to Aalborg Forsyning, which utilises this heat in the DHS.

It appears there are no clear rules regarding who should be responsible for the environmental impacts of using excess heat. As discussed in Section 11.3, there are various ways to define excess heat, each influencing the allocation method differently. The allocating method can not only be complex but also be at risk of double counting environmental reductions due to a lack of standardised definition and allocation method. This in turn can raise questions about accountability and transparency among the users and suppliers of the excess heat. Both the supplier (e.g., Aalborg Portland) and the user (Aalborg Forsyning) might claim the environmental benefits of reduced emissions from using excess heat. This can affect the perception of excess heat, the reporting of it and overall distort the actual environmental benefits achieved.

Traditionally, emissions accountability lies with the primary producers of energy, such as power plants such as Nordjyllandsværket or industrial facilities such as Aalborg Portland. However, since excess heat is not a primary product of the producer, is often unavoidable, and is not used by the producer, it is debatable whether all of the environmental impacts should be allocated to the supplier. On the other hand, the user of the excess heat, Aalborg Forsyning, benefits from the excess heat without contributing to its initial production. Allocating some responsibility to the user could help to promote the efficient use and integration of excess heat in DHS.

Private companies like Aalborg Portland and Nordværk have their own reporting rules and obligations, and these are often guided by corporate sustainability standards. These standards might differ from public or municipal reporting requirements, leading to inconsistencies. These different ways of reporting need to be aligned to ensure that emissions reductions are accurately and consistently reported among the different actors.

Another possibility is to share the environmental impacts between the supplier and the consumer. For this to happen a framework for shared burdens needs to be established. This framework must describe how the environmental impacts should be divided between the two parties, and take into consideration factors such as the proportion of excess heat used and the emissions savings achieved.

In conclusion, it can be said that determining the responsibility for the emissions allocated to excess heat can be a somewhat complex issue that involves multiple stakeholders. Resolving the burden allocation issue between Aalborg Forsyning and its excess heat suppliers needs to be addressed to make more accurate emissions reporting possible and achieve real environmental benefits. Clear definitions, consistent reporting rules, and official guidelines are needed to prevent double counting and ensure that the responsibility for emissions reductions is fairly and transparently shared.

11.5 Lock-in dynamics

As the historical interconnections between carbon-intensive industrial processes have been established in connection to the Aalborg DHS and the planned future developments in section 8, some arguments can be brought up from different perspectives on a (carbon) lock-in dynamic in the DHS as well as insights from the LCA results on the different impact categories and scenarios. Several addressed issues are stated in no particular order.

When connecting the current situation in Aalborg to the different types of lock-ins and their source from within the three forces that influence the the respective lock-ins, the categories mentioned in the theories section can be applied 4.1.

1. Lock-in associated with the technologies and infrastructure that indirectly or directly emit CO_2 and shape the energy supply.
2. Lock-in is associated with governance, institutions, and decision-making that affect energy-related production and consumption, thereby shaping energy supply and demand.
3. Lock-in related to behaviours, habits, and norms associated with the demand for energy-related goods and services.

One of the insights to start with would be a potential smaller but harder lock-in for excess heat supply with Nordværk as waste incineration is not primarily concerned about the output but the handling of waste thus not interested in changing the "fuel". Nordværk is part of another industry and is not as primarily incorporated into the heating supply industry. They would still have to face pressure for changes if radical decarbonisation or burden allocation were to be introduced. When looking at the three different types of lock-in introduced by Goldstein et al. [2023] this can be categorised as a technologies-associated lock-in as the technologies of the excess heat suppliers are designed for other industrial processes than supplying heat to a DHS and thus can not be changed as easily to the liking of the DHS. Cement production has processes that are in development for decarbonisation yet the current practices and technologies are not indicating that the fuel types are changing soon, also the process of heating the clinker, a part of cement production, is CO_2 intensive and not substitutable as of yet. Concerning the Aalborg DHS this is also considered to be a type of technology associated with lock-in.

The price ceiling (Prisloft) even though not planned to protect fossil-based heat sources, price management is effectively slowing down the decrease of reliance on fossil-based excess heat sources by making it harder for Aalborg Forsyning to invest in innovative technologies. This could be categorised as an (even if unwanted) governance-based lock-in dynamic. As it was introduced at times of highly volatile and at times of high fuel prices that made the heat production expensive it should be reevaluated if it is still necessary. Yet the development of the DHS could then raise the heat prices because of the investment costs being directly transferred to the consumer if there is no additional funding for it from either municipality, national institutions or other sources.

In the case of Nordværk, the practice of waste handling by incineration is and has been good practice and as a well-known process could be claimed to be entrenched in Denmark. Even though there are calls for more recycling and circularity of resource streams the current DHS still relies to a substantial degree on the excess heat produced by incineration. Also, Nordværk is relying on compensation which would make it hard to argue for a discontinuation. This can be seen as a lock-in-related behaviour.

As discussed in Section 11.4, it is debatable who should be responsible for the emissions from excess heat production. This depends on the choice of definition, and if impacts would be put on the excess heat suppliers. This would put the suppliers into the dynamic to be pressured into reducing the environmental impacts stemming from their contribution. This might become a dilemma for both the DHS operator and the excess heat provider as the choice to not supply any excess heat might then be more attractive. The currently observed practice gives both sides the option to present environmentally positive results. The operator Aalborg Forsyning claims no emissions and ultimately "*fossil-free*" heat production/supply for example Portland reported that they are contributing excess heat that substitutes primary heat production even though it might be more impactful than the primary heat production technology in a (future) DHS.

EU regulation might in this advanced DHS actually according to these results prolong the use of fossil-based heat. Whilst the idea of excess heat utilisation is deemed favourable for most European DHS, the Aalborg case could experience a *"partial prolonged carbon lock-in"* despite Nordjyllandsværket being phased out by excess heat being the last carbon-based heat suppliers.

In the future, looking at the scenarios there might be a need for a priority decision for cleaner heat produced during summer as it can currently be observed that the excess heat that is steadily provided over the year is fulfilling the demand in summer on its own. The to-be-introduced technologies for heat production are expected to be much cleaner (not only in carbon but in most categories) so it could be argued that heat from those should be preferred. This is currently not practised as Aalborg Forsyning is first and foremost focusing on stable and steady supply which is achievable even only with excess heat.

A radical question could be asked if excess heat should be used at all in DHSs. Considering the results from this study, it is still good to use the available excess heat and incorporate it into the DHS as it otherwise would be wasted anyway. But like other authors are also stating Fontaine and Rocher [2024], it should only be seen as a transitional solution for industries and practices that currently still rely on carbon-intensive practices and technologies. Ultimately there needs to be a shift away from them towards other fuels and practices to not only become more efficient with emissions but to optimally get rid of them completely.

When connecting the current situation in Aalborg to the different types of lock-ins and the key aspects of the respective lock-ins, the categories mentioned in the theories section can be applied 4.1.

The academic literature indicates that the definition of excess heat is not entirely clear. Additionally, the current definition of (Energystyrelsen, Danish Law, EU) and handling of the term excess heat seems to not account for the struggle of burden allocation. It is thus hard to have a clear allocation of burdens between producers and users of excess heat. This problem overshadows not only the CO_2 reductions but other less addressed impacts from the same proceeds. This situation is derived from the past and bears the danger of double counting the achieved reductions in impacts and stands in the way of actual successful reductions. The described problems can be categorised as symptoms/signs of inertia stemming from the preexisting carbon lock-in TIC as it makes it fairly easy for contributors and beneficiaries of it to proceed with the current way of production, not having to change a lot to comply with the requirements. Whilst this is currently still producing some actual reductions it must be emphasised that with the current practice, it is assumed to not be possible to achieve full "fossil-free" operations in the future as claimed as the burden of using fossil fuels is just shifted to other parts of the system which are not acknowledging those burdens themselves.

11.6 Further research

This section will present what other future studies could investigate further based on the findings, analysis and discussion of this study.

As presented in Section 9.3.3, the future main heat productions in the DHS of Aalborg municipality will be a seawater heating pump and electric boilers. All of these will use electricity as the primary fuel, and it can therefore be said that the DHS of Aalborg municipality will undergo electrification in the future. The impacts of this change on the DHS are not thoroughly analysed in this study. It could however be a focus of a future study to conduct an LCA on the electrification of the DHS in Aalborg municipality or elsewhere where it is happening. Also here it would be interesting to include a time dimension in the LCA since the electricity mix most likely will change over several years and also for different months or seasons during a specific year.

This study does not in-depth address or investigate the responsibility for emissions from excess heat production, but it is an important aspect that should be looked into in future studies. Future research could explore how current EU, national, and local policies allocate these emissions and how potential regulatory changes could clarify this responsibility. Key areas for further study include stakeholder interviews, case studies of regions with implemented policies, and the economic impacts of different emission allocation approaches. Additionally, future research could consider the feasibility of monitoring and reporting emissions from excess heat production and analyse the legal and ethical implications of assigning responsibility. This research would help establish a clearer framework for managing emissions from excess heat production.

It is encouraged and recommended to conduct further research on the dynamics that can create, maintain and break lock-ins for this case. Yet due to time and resource constraints and the more interview-focused approach other lock-in articles use, it is deemed adequate to be done in a separate specifically designed research project. In this study, the lock-in theory is used as a supporting background to contextualise the surrounding aspects of the involved forces that affect the system that is the subject of the LCA and what implications the findings of analysing the environmental impacts can have on the involved forces reversely.

12 Conclusion

This conclusion contains a summary of the findings of the study and answers the main research question by first answering the three sub-questions:

1: How can an hourly LCA model be used to support decision-making? An hourly LCA model is achieved in this study, by utilising hourly heat supply and demand data along with environmental impact factors for each heat supplier. This results in environmental impact results that vary throughout time, reflecting changes in the heat supply. This can be used to see how small or big changes in the DHS affect the environmental impact of the system. By utilising an hourly LCA model, the connection between the DHS and its environmental impact is made clearer, which can be used to support decision-making.

2: How do varying definitions of excess heat affect the environmental impact associated with its utilisation in district heating systems?

This study has shown that there is no universally agreed-upon definition of excess heat and how it should be treated in terms of its potential environmental impact. The current standard approach often views excess heat as burden-free, with no environmental impact associated. While this approach does seem natural, as the excess heat is a waste product and would otherwise not be used if not utilised in the DHS, several issues can be found with this approach. In this study, environmental impacts are allocated to the excess heat, based on its share of the total energy production of the excess heat source. Using this approach, the results show that allocating environmental impacts to excess heat has a large impact on the overall impact of a DHS. Furthermore, it shows that it is not only negative impacts that occur but due to the substitution of the primary heat supply with the excess heat, positive impacts can also be seen. As such, by viewing excess heat as burden-free and therefore not analysing its impacts further, decision-makers can become blind to both the negative and positive impacts of using a specific source of excess heat. This can also have a negative impact on the future development of the DHS, as the perception of excess heat as burden-free can lead to a lack of incentive to improve the DHS. The results further show that the environmental impact of excess is largely dependent on the primary heat supply. When the primary heat supply has a large negative environmental impact, the excess heat appears more beneficial compared to when the primary heat supply has a low negative impact. In other words, the environmental impact of excess heat increases, as the environmental impact of the primary heat supply decreases, and vice versa.

3: What are the potential barriers and opportunities for minimising the environmental impact of the district heating system when utilising excess heat?

By analysing the case of the Aalborg municipality's DHS and its most relevant stakeholders on the background of their development concerning its involvement in the DHS, their path-dependency from the past, and lock-in dynamics a context in which the LCA and its analysed impacts on the DHS occur was created. The complex interplay of the stakeholders is not only on the technological level but also how institutions, current governance, and practical factors are contributing and have contributed to carbon lock-in dynamics has been described and contextualised for the Aalborg DHS. The discussion stresses different angles and interests in the matter as the DHS with its different involved technologies of external and internal actors emphasises issues that should be addressed to include the issues of proper burden allocation and incorporation of the varying environmental impacts in the operation of the DHS. Possible measures could include reevaluating governance practices, recommending the prioritisation of less environmentally impactful heating in the operator's daily activities, and addressing systemic issues in burden allocation to achieve credible decarbonisation.

This leads to the answer to the main research question:

"***How does the utilisation of excess heat influence the environmental impact of the district heating system in Aalborg municipality?***"

This study has shown that the topic of excess heat is not as straightforward as it may seem. While utilising excess heat in DHSs is an advantageous use of an otherwise wasted resource, it is necessary to not view excess heat as burden-free. Excess heat can lead to a decrease in a DHS's overall environmental impact, however, without attributing environmental impacts to the excess heat, the exact effect can not be determined. If the DHS is to be planned as impact-free as possible, it is necessary to also include the environmental impacts of excess heat, to make the most well-informed decisions possible. In Aalborg's case, as the formerly locked-in focus on carbon-based heat solutions and the new developments already showing an "unlocking dynamic" by the inclusion of innovative, less impactful changes to the DHS, it can be claimed that a discussion about more clear rules and practices about the considerations of these impacts could add to a more clear path towards the goal of avoiding unaccounted further impacts. The proposed method in this study allocates a certain environmental impact to the excess heat, revealing a more nuanced view of the resource. Using this approach, excess heat sources can be differentiated from each other, allowing for more informed decisions on how best to plan the DHS. The consequential approach used in this study further shows the need for a continuous evaluation of the environmental impact of the excess heat, as the relative impact increases when the primary heat supply becomes less impactful.

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Interview with Silas Alvin Hupfeld A

A.1 Interview with Silas

Summary of timestamps and subjects covered in the interview with Silas Alvin Hupfeld who is the team leader of strategic energy planning at Aalborg Forsyning.
Date: May 8th, 2024. Scheduled from 11:00 - 12:00.
Place: Online via Microsoft Teams.

Attendees of the interview: Mathias Gustavsen, Frederik Luft and Magnus Mikkelsen and the interviewed Silas Alvin Hupfeld.

The interview lasted 55 minutes and was recorded with approval from Silas Alvin Hupfeld.

Only the project group has access to this recording. The following summary of the interview includes timestamps and the main points of the subjects discussed. This ensures that the information gathered can be accurately cited and used in the report.

Theme	Timestamp	Notes
Data	00:00 – 01:10	Quick talk about if we got the data and what is missing. This will be expanded upon later in the interview.
Presentation of Silas Alvin Hupfeld	01:10 – 02:31	Role and Responsibilities Strategic Energy Planning Department Focuses on long-term planning and ensuring that heat supply meets demand. Also has some say in choosing future heat production units
Future scenario	02:31 – 10:00	Impact of CHP shutdown at the end of 2028. Nordjyllandsværket supplies around half of the heat Replacement of heat production by various sources: Seawater heat pump: 132 MW and 177 MW (primary heat production). Additional heat pump lines to make up the difference. 150 MW (3x50 MW) electric boilers for peak and cheap electricity. 200,000 cubic meters of extra water storage (steel). 6 MW wastewater heat pumps. Deep involved with the Fjord PtX Potential CCUS Specific sources are still somewhat undefined A data centre in Aalborg was mentioned but not considered significant by Silas.
Strategic plans and reliability	10:00 – 14:42	How large a share is Aalborg Forsyning willing to be dependent on private companies to produce heat. The previous strategy (2017) aimed for 40% excess heat, nearly realized. Excess heat is considered secondary; peak and reserve boilers ensure reliability. Excess heat suppliers are not obligated to produce heat when it is needed, but they can ask them. Peak and reserve boilers to take over. It can supply all the heat even with no excess heat. Security of supply is prioritised, considering technological, policy, and economic implications.
Price ceiling impact	14:42 – 20:10	The current practice of price ceiling (110 kr. per GJ) potentially inhibits innovation. This is included with all the infrastructure and other units needed. Discussion on cost dynamics and ministry involvement. The price ceiling intends to make sure that utility companies do not pay too much for heat. But it instead stops a lot of projects regarding excess heat.
Data and supply-demand	20:10 – 31:20	Going through the data that the project group has received. Approximately 6% shortfall in supply. Peak load boilers produce the rest of the heat. It could also be from storage. CHP is most likely out because of maintenance.

		If the electricity price is very low, they use their electric boilers. But it can only cover a small part of the demand. In the case of low demand being met, then assume that the rest is produced by a boiler (gas or electric). Talk about "brændselsfrit" or fuel-free and what it is. Says it is excess heat.
Infrastructure	31:20 – 39:50	Water pumps (69 currently, with potential increases). Types and capacities of water pumps. System loss (17% yearly) factored into demand calculations.
	39:50 – 44:45	Challenges with using fossil-intensive providers of excess heat. Is the DHS still fossil-free even though Aalborg Portland uses fossil fuels to produce heat. The heat will be produced no matter what, and that is the argument why excess heat is fossil-free. Fossil burden allocated to suppliers (e.g., Portland). Nobody is taking responsibility for the environmental impacts of excess heat. Political and strategic implications of this allocation.
Target audience	44:45 – 50:20	Point out black spots in the understanding of excess heat. In relation to Denmark being fossil-free in 2050 then the emissions of excess heat must be included. Someone must take responsibility. Clarifying responsibilities for fossil-based impacts. Talk about other DHSs in Denmark. The heat is there no matter what. Allocation of burdens and the need for increased awareness. Strategic impact considerations and potential oversight of actual environmental impacts. Raise awareness of emissions of excess heat.
Environmental impact in a DHS	50:20 – 54:06	How are the environmental impacts included in planning DHSs? Discussion on electricity used in DHS. CO2 is the main impact factor looked at. What is the environmental impact of electrifying the DH in Denmark?
Outro	54:06 – 55:28	

Figure A.1. Protocol of the interview with Silas Alvin Hupfeld

B Results from the LCA

This appendix shows Figure 10.2, 10.3 and 10.4 in enlarged versions.

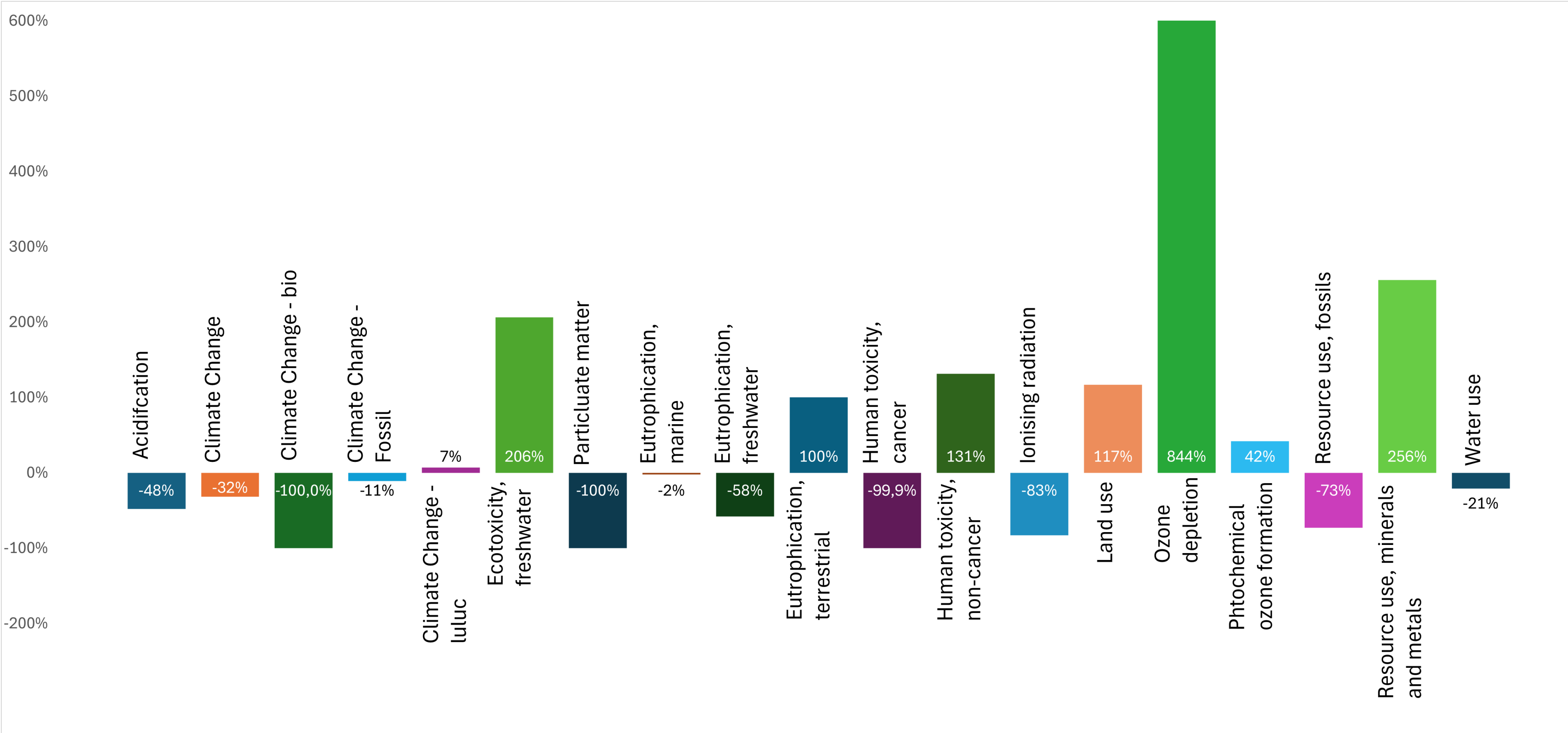

Figure B.1. Difference between results from the 2030 scenario and baseline

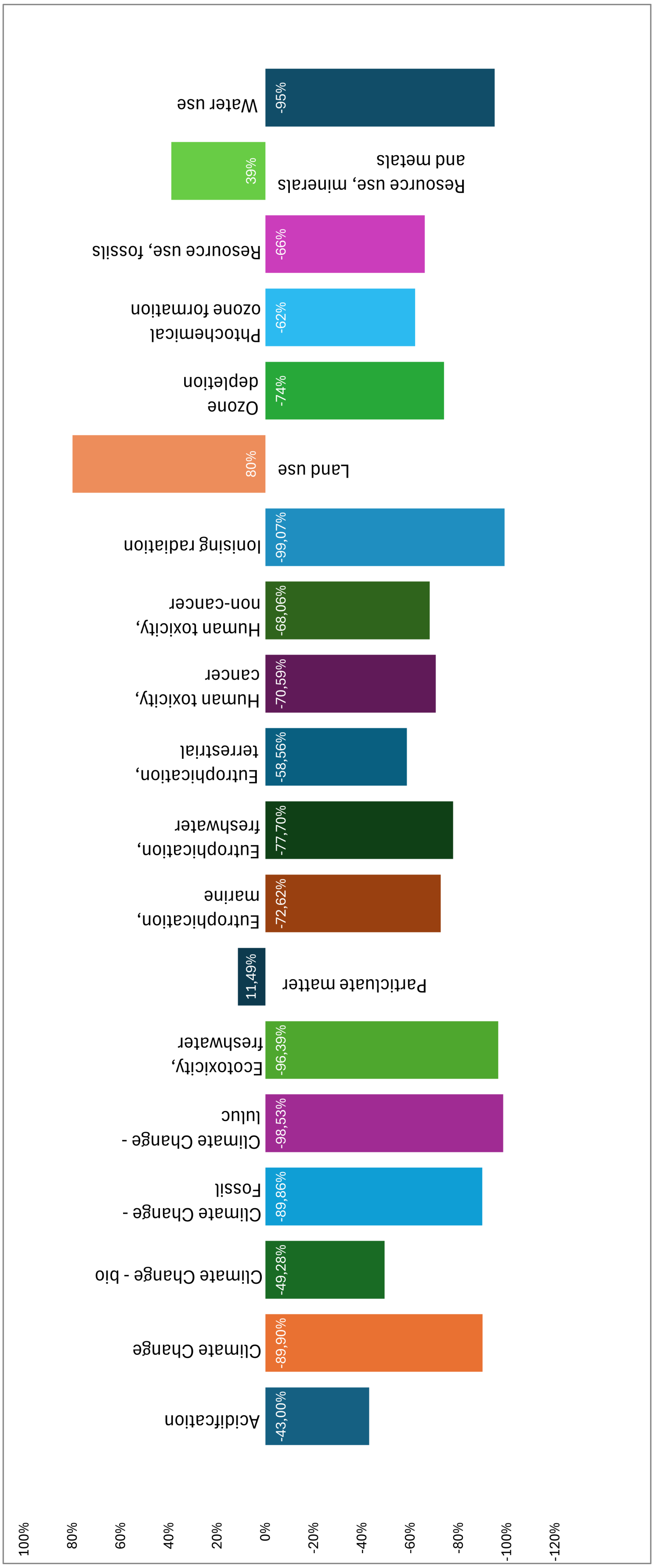

Figure B.2. Impact on future scenario results when no impact from excess heat

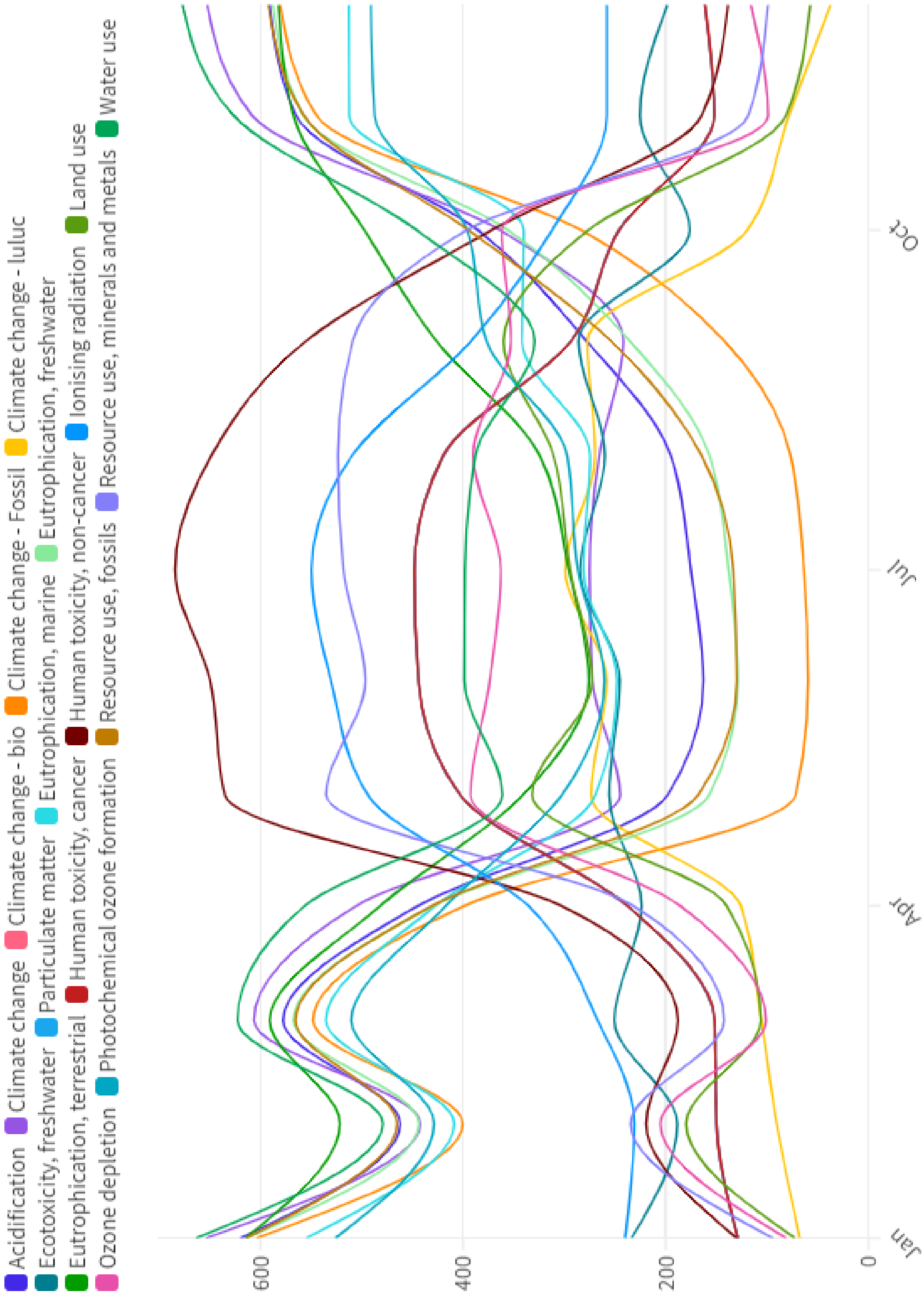

Figure B.3. Environmental impacts of producing 1 kWh of heat throughout 2023