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Pettersson, Malin

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LUND UNIVERSITY

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

Biobased Combined Heat and Power Production in Sweden
– Opportunities for and Challenges to Sustainability from the Plant Operator Perspective

MALIN PETTERSSON
FACULTY OF ENGINEERING | LUND UNIVERSITY

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– Opportunities for and Challenges to Sustainability from the Plant Operator Perspective

Malin Pettersson

Department of Technology and Society

Faculty of Engineering

2023

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Abstract
Although combined heat and power (CHP) production in Sweden is already largely decarbonised, this technology has further potential to alleviate pressing environmental concerns. Today, biobased CHP plants connected to district heating (DH) grids dominate the Swedish residential heating sector. The societal context in which CHP plants operate is, however, subject to continuous change. New aims and requirements concerning decarbonisation and resource efficiency are being discussed and implemented in the political arena to promote the shift towards a sustainable energy system. These include the cascading use of biomass, bioenergy carbon capture, support schemes for innovative investments, life-cycle-based climate performance regulations, and circularity demands. Such shifts affect the operation of CHP plants and can provide new opportunities and challenges that have not yet been investigated. Neither are the consequences fully understood in the scientific or political community. This thesis presents an investigation of the opportunities and challenges facing CHP plant operators within the context of a shift towards a sustainable energy system.

Issues of environmental relevance were investigated through a case study of a Swedish wood-fuelled CHP plant. The recycling of wood ash to forest soils after logging residue outtake is recommended to close the loop for forest nutrients and ensure forest production. However, co-incineration of waste wood and forest fuels in the Swedish DH sector was found to inhibit wood ash recycling, due to pollutants in the ash from waste wood. It was also found to be an overlooked challenge in the transition to a circular bioeconomy, where waste wood is utilised to produce energy. Other important issues in a circular bioeconomy are the efficient use of biomass and the production of high-value biobased products. CHP plants are dependent on a stable heat demand to operate efficiently. The addition of a pyrolysis unit, a heat-demanding process, to produce liquid biofuels that could increase the uptime and open up an additional market for CHP plants as biorefineries was studied. Life-cycle analysis showed this to be technically feasible at the CHP plant studied, and to substantially improve the overall greenhouse gas (GHG) benefits. Negative GHG emissions have been deemed by the IPCC to be an important complement in achieving net zero GHG emissions. Biobased CHP plants can contribute to negative emissions through the implementation of carbon capture. However, these technologies are energy-demanding, and thus reduce the energy efficiency of the plant. It was shown that the carbon mitigation potential of installing equipment for carbon capture or liquid biofuel production was highly dependent on which energy sources compensate for the changes in the value chains, which is in turn dependent on the decarbonisation of the surrounding energy system. An important outcome of the work presented in this thesis is the identification of existing and emerging opportunities and challenges related to sustainability in biobased CHP plants, which can contribute to, or hamper, the fulfilment of environmental goals. The studies on these opportunities and challenges can prove valuable knowledge for other countries and regions that are planning to develop biobased CHP plants with DH grids. Successful navigation of these opportunities and challenges by policy makers and CHP plant stakeholders will be instrumental in ensuring a decarbonised and resource-efficient energy system.

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Like it or not, for the moment the Earth is where we make our stand.

- Carl Sagan

Contents

Abstract

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these opportunities and challenges can prove valuable knowledge for other countries and regions that are planning to develop biobased CHP plants with DH grids. Successful navigation of these opportunities and challenges by policy makers and CHP plant stakeholders will be instrumental in ensuring a decarbonised and resource-efficient energy system.

Populärvetenskaplig sammanfattning

Även om kraftvärmeproduktionen redan är i stort sett koldioxidneutral i Sverige har denna teknik en potential att ytterligare bidra till angelägna miljöfrågor. Idag dominerar biobaserade kraftvärmeverk anslutna till fjärrvärmenät den svenska bostadsvärmesektorn. Det samhälleliga sammanhang som kraftvärmeverken verkar i är ständigt föremål för förändringar. Nya mål och krav gällande utfasning av fossila bränslen och resurseffektivitet, som stödjer en förändring mot ett hållbart energisystem, diskuteras och implementeras på den politiska arenan. Dessa inkluderar kaskadanvändning av biomassa, bioenergiavskiljning av koldioxid, stödsystem för innovativa investeringar, livscykelbaserade klimatföreskrifter och krav på cirkularitet. Sådana förändringar förändrar verkligheten för kraftvärmeverksföretagen och kan innebära nya utmaningar och möjligheter som ännu inte har kartlagts, och konsekvenser som inte helt förstås, i det vetenskapliga eller politiska samfundet. Denna avhandling omfattar en undersökning av möjligheter och utmaningar för en kraftvärmeoperatör inom ramen för en förändring mot ett hållbart energisystem.

Olika frågor av miljörelevans studerades med hjälp av en fallstudie av ett svenskt trädbränsleeldat kraftvärmeverk. Återföring av träaska till skogsmark efter skogsbränsleuttag rekommenderas för att stänga kretsloppet för näringsämnen och säkerställa skogsproduktion. Samförbränning av skogsbränslen och returträ i den svenska fjärrvärmesektorn visade sig förorena träaskan och därigenom hämma återföring av den. Det visade sig också vara en förbisedd utmaning i övergången till en cirkulär bioekonomi. En annan viktig fråga för en cirkulär bioekonomi är effektiv användning av biomassa och produktion av högvärdiga biobaserade produkter. Parallellt är kraftvärmeverken beroende av ett stabilt värmebehov för att vara i gång. En utredd lösning är att lägga till en pyrolysenhet, en värmekrävande process för att producera flytande biobränslen, som skulle kunna öka drifttiden för kraftvärmeverk och öppna ytterligare en marknad som bioraffinaderier. Detta har visat sig vara tekniskt genomförbart vid fallstudiens kraftvärmeverk och avsevärt minska de totala växthusgasutsläppen, när de uppskattas i olika livscykelanalyser. Negativa växthusgasutsläpp har ansetts vara ett viktigt komplement av IPCC för att nå nettonollutsläpp av växthusgaser. Biobaserade kraftvärmeverk kan bidra till negativa utsläpp genom att installera koldioxidavskiljningsteknik. Dessa tekniker är energikrävande och minskar anläggningens energieffektivitet. Potentialen att reducera koldioxidutsläpp visades vara starkt beroende av vilka energikällor som kompenserar för förändringarna i värdekedjorna, vilket i sin tur är beroende av utfasning av fossila bränslen i det omgivande energisystemet. Detta visade sig gälla både för att installera koldioxidavskiljning och för att producera flytande biobränsle genom pyrolys. Ett viktigt resultat av denna avhandling är belysandet av befintliga och framväxande möjligheter och utmaningar kopplat till hållbarhet för biobaserade kraftvärmeverk, som kan bidra till, eller hämma, uppfyllandet av miljömål beroende på hur de hanteras. För andra länder och regioner som vill installera biobaserad kraftvärme med fjärrvärmenät kan de undersökta tillvägagångssätten för att hantera dessa möjligheter och utmaningar visa sig vara värdefull kunskap. För beslutsfattare och intressenter i kraftvärme kommer en framgångsrik navigering av dessa möjligheter och utmaningar vara avgörande för att säkerställa en fortsatt utveckling mot ett koldioxidfritt och resurseffektivt energisystem.

List of publications

This thesis is based on following publications, which will be referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

I. Pettersson, M, Björnsson, L & Börjesson, P, 2020. *Recycling of ash from co-incineration of waste wood and forest fuels: An overlooked challenge in a circular bioenergy system*, Biomass & Bioenergy, vol. 142C, 105713.

II. Björnsson, L, Pettersson, M, Börjesson, P, Ottosson, P & Gustavsson, C, 2021. *Integrating bio-oil production from wood fuels in an existing heat and power plant – evaluation of energy and greenhouse gas performance in a Swedish case study*, Sustainable Energy Technologies and Assessments, Volume 48, 2021, 101648.

III. Pettersson, M, Olofsson, J, Börjesson, P & Björnsson, L, 2022. *Reductions in greenhouse gas emissions through innovative co-production of bio-oil in combined heat and power plants*, Applied Energy, vol. 324, 119637.

IV. Pettersson, M, & Björnsson, L. *Greenhouse gas emission mitigations through add-on technologies for biobased heat and power – a comparison of BECCS and liquid biofuel production*. Manuscript to be submitted to the International Journal of Greenhouse Gas Control.

The author's contributions (CRediT)

Paper I - Conceptualization, Investigation, Methodology, Data curation, Writing – review & editing, Visualization.

Paper II - Investigation, Methodology, Writing – review & editing.

Paper III - Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration.

Paper IV - Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration.

All authors read and approved the final manuscripts.

Other relevant publications

Pettersson, M, & Björnsson, L, 2019. *Aska från samförbränning av returträ och andra biobränslen: Förekomst av önskade näringsämnen och oönskade spårämnen vid en fallstudie av Örtofta kraftvärmeverk*. (Rapport 112 ed. 1) Miljö- och energisystem, LTH, Lunds universitet. (In Swedish)

Björnsson, L, Gustavsson, C, Pettersson, M, Börjesson, P, Ottosson, P, & Samuelsson, J, 2021. *Bioolja från befintliga kraftvärmeverk – en systemstudie: Sammanfattning av ett forskningssamarbete mellan Lunds Tekniska Högskola, Karlstad Universitet och Kraftringen Energi*. (Rapport 123 ed. 1) Miljö- och energisystem, LTH, Lunds universitet. (In Swedish)

Pettersson, M, 2022. *Longer Operating Time and Great Climate Benefit in Bio-oil Production at CHP Plants,* Proceedings of The European Biomass Conference and Exhibition, Online, May 2022.

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First, a little introspection. I have come to realise that writing a thesis is a very personal but, at the same time, revealing process. At times I have picked my own thought-processes and behaviours apart, questioned them just as I have done with my research topic; wondered what in world I am looking at and how I am supposed to do anything valuable with this. Luckily, I have had the help of many wonderful people in bringing this project home.

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And little Åke, my bundle of joy, who always brightens my day.

Malin,

March 2023

1 Introduction

1.1 The current and historic role of biobased combined heat and power production in the Swedish energy system

In 2022, thermal energy demand in buildings made up twenty-five percent of the total global final energy demand. Only 14.7% of that demand was supplied by renewable sources [1]. The need for decarbonisation and efficiency measures in residential and space heating is imminent, to reduce its effect on the environment. Many of these measures have already been implemented in Sweden through the introduction of biobased combined heat and power (CHP) plants, also called co-generation plants, connected to district heating (DH) systems, instead of fossil fuel-based heating.

The development of decarbonisation was prompted by a desire for greater independence from oil imports in the 1970s. The desire drove a shift from fossil-fuelled heat production to the use of logging residues, forestry by-products (such as sawdust and bark from sawmills and residual heat from pulp and paper mills) and household waste. Today, Swedish heating fuels are almost completely fossil-free. In 2020, the use of fossil fuels in the heating sector (including CHP) amounted to only 1.5% of the total fuel use [2]. A small share of back-up fuels used at peak load are still fossil-based [3]. The energy input and fossil CO_2 emissions attributed to DH in Sweden between 1970 and 2020 are shown Figure 1. This development has brought about a significant reduction in the impact of the Swedish heating sector on the climate; the greenhouse gas (GHG) emissions from heating decreased by 90% between 1970 and 2014 [4]. Sweden now has the lowest average carbon footprint for residential heating in the European Union (EU) (8.1 g CO_2-eq/MJ in 2015) [5], and is continuing to decline [6].

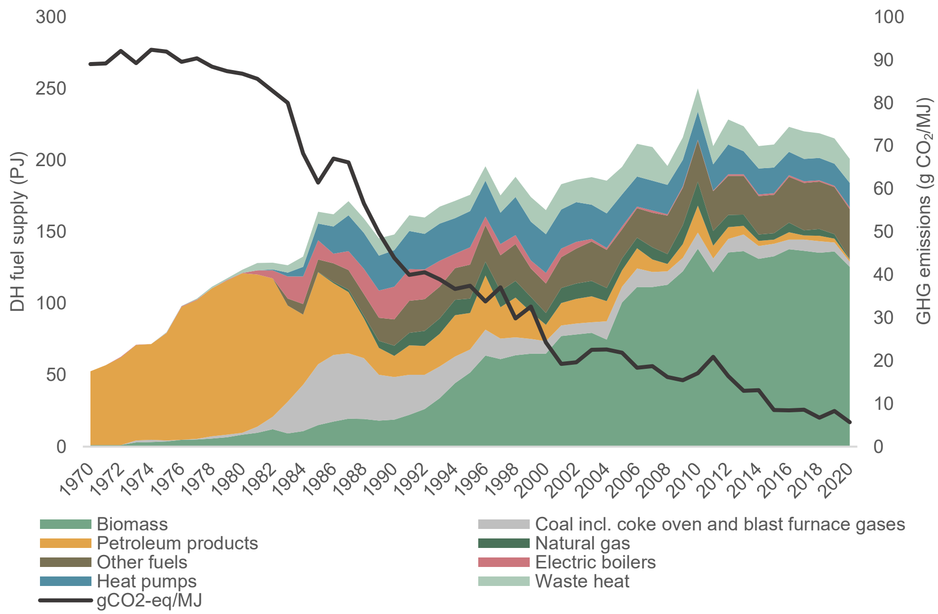

Figure 1. Energy used in the production of DH in Sweden (PJ) [7] and CO_2 emissions from the fossil energy input to Swedish DH systems (statistical data [8] adapted using the calculation method described by Ericsson & Werner [4]).

The major share of residential heating in Sweden, around 60%, is supplied using approximately 556 separate DH grids [4,9]. Currently, 110 biomass and waste-fired CHP plants are connected to 72 of the DH grids [10]. Thus, biobased CHP plants connected to DH grids plays an important role in the contemporary Swedish heating sector. Figure 2 shows the development of CHP plant installations in Sweden currently in operation and their heat and power output, averaging around 65 and 22 MW, respectively. It can be noted that the classification of CHP plant in this thesis do not include pulp and paper mills. Much of the running CHP capacity was installed during 2005-2015, effectively increasing the resource efficiency of the fuels used for residential heating. Out of the Swedish electricity production in 2021, 9% were produced in CHP plants [11].

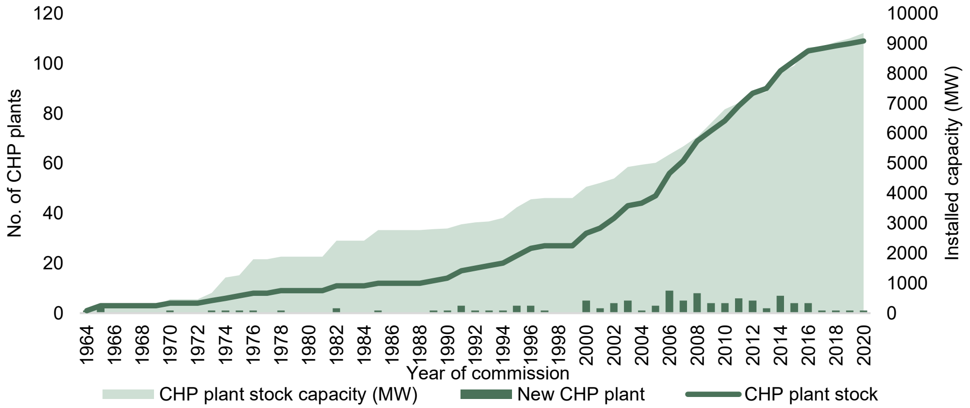

Figure 2. The number of CHP plants commissioned in Sweden between 1964 and 2020, and their installed heat and power capacity [10].

Biobased CHP could be a key technology to support in policies for decarbonised and energy efficient heat and power production, given the imminent global need and the important role the technology has played in Sweden. One reason in that CHP plants can achieve high energy efficiencies of about 90%. High-temperature, high-pressure steam is used for electricity generation, and the remaining steam is used to heat the DH medium. The combined production of heat and power is promoted in the EU Energy Efficiency Directive to increase energy efficiency within the EU member states [12]. Another reason is fossil fuels still dominating CHP production in Europe [13], and there is a large need for switching to renewable fuels.

In Sweden, however, the market for heat and power from biobased CHP plants is more or less saturated [14]. Most investments are made to replace old plants [3]. In parallel, there is a common ambition in the heating sector to further contribute to decreasing the GHG emissions [15]. In other words, the CHP and DH infrastructure in Sweden is already highly developed, and there is no further demand for forestry residues for centralised heat production. Thus, the task facing the Swedish energy sector is to ensure the continued delivery of decarbonised heat and power, and to further develop CHP plants to gain even greater GHG benefits.

1.2 New roles and demands emerge for biobased CHP

Biobased CHP will remain important in the foreseeable future, as a producer of low-carbon electricity and DH. There are also opportunities for the CHP plant operators, within the transition to a bioeconomy, to contribute and strengthen their role in the energy system. An example is by refining biomass to high-value products and intermediates through different technology configurations (see for example [17–20]). Another opportunity is CO_2 capture in CHP plants, thereby becoming a producer of negative emissions. An IPCC Assessment Report published in April 2022 (AR6) stresses that carbon dioxide removal (CDR) methods must be implemented as soon as possible if we are to achieve climate goals [21]. CDR is defined as anthropological activities that remove carbon dioxide from the atmosphere and store it durably in reservoirs or products (ibid.). CDR methods includes bioenergy carbon capture and storage (BECCS). In densely populated areas the CHP plants will also have a key role in frequency control and balancing intermittent renewable power production [22–24]. In realising these opportunities, steering measures on European and Swedish levels are being put forth, which include demands on environmental sustainability (including life cycle GHG emissions). An example in the EU Innovation fund (IF), the largest fund in the world for financing innovative climate mitigation projects [25]. Another example is the EU Renewable Energy Directive (RED) promotes increased production of renewable energy with low GHG emissions [26].

Beside the opportunities, there are also emerging challenges for CHP plant operators. One example is the heating load in Swedish DH grids being expected to decrease in the coming decade. There are multiple reasons for this trend. Energy efficiency measures in buildings, climate change, and a rise in installation of domestic heat pumps for space heating together lowers the need for heating [3,27]. Another example of a challenge is the implementation of the cascade principle of biomass in EU directives, driven by biomass being a limited resource. In the third revision of the EU RED, currently in trialogue before final adoption, the sustainability of some solid biofuels that are used in the Swedish DH sector are questioned. The use of primary woody biomass, i.e., all wood removed from forests including logging residues, for energy purposes has been argued to be unsustainable by the European Parliament [28], and should not be financially supported. The circular management of wood ashes and forest nutrients are examples of ongoing challenges. The need for bringing wood ashes back to forest soil to close the loop on forest nutrients has been known for some time [29,30], but the recycling rate remains low [31]. The urgency is exacerbated through the increased need for sustainable forest biomass feedstock. There are more European policies that could affect the environmental performance of biobased CHP operators, such as the EU waste directive [32], the regulation for achieving climate neutrality [33] and action plan for circular economy [34]. The examples of opportunities and challenges illustrate the complexity and range of important aspects for sustainable development of biobased CHP plants. Thus, aspects of environmental sustainability in relation to the CHP sector needs to be further studied from both a deeper and broader energy system perspective.

1.3 The important lens of the CHP plant operator

Biobased CHP plants are predicted to have important roles in a 2050 decarbonised energy system [34], and research and policy on the future for CHP is developing, offering many options for CHP plant operators, regarding both existing plants and new investments. At the same time, biobased CHP often involve large investments, compared to other existing heat supplying technologies for DH grids [39]. Policies and CHP plant stakeholders need to ensure that the existing and emerging opportunities and challenges of the biobased CHP operator are successfully navigated, to maximise the contribution of the technology to a biobased economy and safeguard their important role in the community.

One approach to determine the consequences of various policy regulations and instruments that aim to contribute to sustainability goals in the energy system, is to include the perspectives of actors and stakeholders. Including public stakeholder perspectives can lead to formulation of more relevant problem formulation for sustainability transitions in society [35,36], due to for example better local and regional knowledge. This highlights the prospect of using a CHP plant operator perspective to identify and understand opportunities and challenges to a sustainable energy system.

The perspective of existing DH companies has been used in exploratory case studies for identifying and highlighting details on drivers and challenges for sustainable energy system goals in current operations [37,38]. Since the conditions for the Swedish CHP operators are partly similar but could also vary, for example concerning the length of heating season and availability of different biomass feedstocks [23], policies could have different consequences and benefits for biobased CHP operators. It is thus imperative for CHP operators to understand the consequences of regulatory and technology development which may influence future operations. Vice versa, regulators and policy makers must understand what effects regulations have on the actors in the CHP sector.

Pertaining such knowledge may also be useful for governmental bodies and stakeholders in other countries where the aim is to use decarbonise the heating system. A decarbonised heating system brings importance and relevance to identifying and resolving sustainability challenges beyond switching to renewable sources. The knowledge provided by a case study in Sweden, where the development of renewable heating is advanced, will be useful in other countries and regions with similar conditions planning to shift their energy system towards the sustainable use of CHP, or the development of existing plants. In particular in regions with boreal forests, where the role of wood-fuelled CHP plants could be significantly enhanced [14].

1.4 Aim and research questions

The central aim of the work presented in this thesis was to increase our knowledge on the conditions for, and potential of, biobased combined heat and power production in the transition to an environmentally sustainable energy system. To this end, the following three research questions were posed:

1. Which are the key issues in achieving a sustainable circular material chain for wood-fuelled CHP plants?
2. What are the conditions and potential for pyrolysis technology integration to extend the CHP plant operating season and achieve wider energy system decarbonisation?
3. How do energy system decarbonisation levels affect life-cycle GHG emissions from BECCS integration at CHP plants?

1.5 Scope and outline

The aspect of challenges to the sustainability of biobased CHP plants is broad and many aspects must be analysed. This thesis focuses on aspects of environmental sustainability and pathways for realising policy and steering measures for wood-fuelled CHP. The scientific contributions of this work have the focus of the energy company operation in relation to the Swedish contemporary energy system. As specified in the research questions above, the thesis covers three research subjects, described in four papers (**Papers I-IV**). The research subjects are related to the sustainable development of a Swedish wood-fuelled CHP plant, i.e., they either help or hamper the CHP plant in achieving nationally set environmental goals, in their current and near-future operation.

The CHP plant at Örtofta in southern Sweden was used in formulating the research questions and constructing the case studies described in this thesis. This CHP plant is operated by the energy company Kraftringen Energi AB, owned by the local authorities (the municipality of Lund, Lomma and Eslöv) [40]. There are several factors that made this plant a suitable and interesting case to study. For example, the heat produced at the Örtofta CHP plant and distributed through the DH grid has one of the lowest GHG emission factors in Sweden [41]. The plant is solely operated on biofuels; different types of wood fuels are co-incinerated. The shorter heating season in southern Sweden, where the Örtofta plant is situated, makes the plant an especially suitable case for investigating opportunities for increasing plant uptime. The opportunities and challenges identified in the current and future operation of the Örtofta CHP plant, and the results of case studies are presented in the wider energy systems perspective. The focus was on issues in the near future, as these are most relevant and pressing for the plant operator. The issues dealt with in the papers are presented in Figure 3, where the lighter boxes contain aspects that are relevant for the CHP operator from a sustainability perspective. The outer boxes contain the areas related to these CHP operator aspects, that were identified as being of scientific relevance to investigate further, and consequently explored in the four papers. Each area is represented and discussed in a separate chapter of this thesis (Chapters 3,4 and 5), including the contributions from each paper.

The following factors are not included in the scope of thesis: financial and social sustainability (such as energy access and affordability), sustainable forestry including forestry carbon balances and biodiversity, the operator perspective of heat-only boilers, and household waste-fuelled plants.

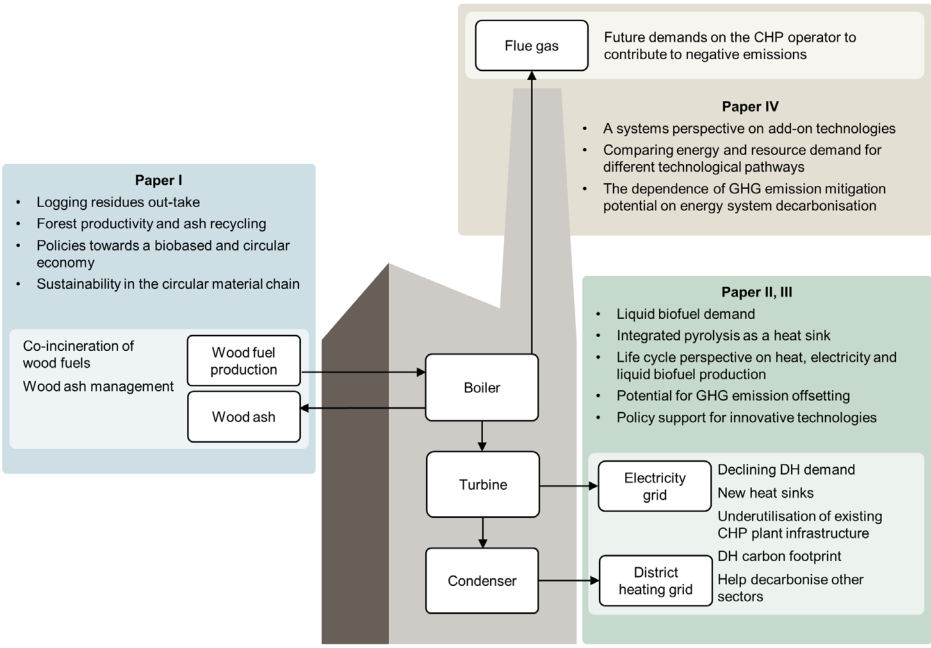

Figure 3. Sustainability-related aspects of the CHP plant operator (light boxes) and identified areas further explored in papers (darker boxes).

Chapter 2 contains a brief description of the research process and approaches used in the thesis. Chapter 3 describes the problems associated with recycling ash from wood-fuelled CHP plants, and the problem this poses to achieving circular material goals, including the contributions from **Paper I**. Chapter 4 discusses the impact of including a unit for the pyrolysis of wood fuels at a CHP plant on the continued delivery of low-carbon heat and power, and the potential for producing liquid biofuels to help decarbonise the transport sector (**Papers II** and **III**). Chapter 5 deals with the possible effects of implementing carbon capture at a CHP plant on the delivery of heat and power, and on the potential for negative GHG emissions (**Paper IV**). The main findings are summarised in Chapter 6, and an outlook on further research is provided.

2 Research approach and process

This chapter describes the general approach used, and methodological considerations applied in this thesis. The aim is to motivate the methodological choices and assumptions made in the various studies. Details pertaining to each study can be found in the relevant papers.

2.1 Collaboration with the operator

The research questions were formulated through a collaboration with the energy company Kraftringen Energi AB and applying a broad energy systems perspective. These two viewpoints allowed for the identification of research questions that are relevant both for the individual energy company, and for the transition to a sustainable society in general. A process including collaboration with both academic and non-academic actors (also called transdisciplinary co-production of knowledge), is an acknowledged approach to gain relevant knowledge to achieve sustainability transformations of society, for example through promoting more informed and equitable decision-making [42]. Jacobi et al [43] argue that knowledge obtained from research aimed at sustainability transformations cannot be utilized without discussions between academic and non-academic actors. Throughout the course of this work, dialogue and workshops involving experts from Kraftringen Energi AB were used to qualitatively identify interesting sustainability-related phenomena at the plant. Literature surveys of relevant policy and steering measures were conducted to identify intersecting questions, i.e., research questions that are relevant from the academic and the broader societal perspectives. Apart from identifying and discussing the relevance of the research questions to the operator, collaboration with Kraftringen Energi AB served to confirm the suitability of the methodology, using the Örtofta CHP plant as a case study (an aerial view of the plant can be seen in Figure 4). The results were also discussed and verified with experts from Kraftringen Energi AB.

Figure 4. The Örtofta CHP plant. Photo: Peter Duvander, Kraftringen Energi AB.

2.2 Methodology considerations

Research approaches were designed to analyse general, overarching problems of societal importance concerning biobased CHP; specifically, ash recycling, a decline in heat demand, decarbonisation of the transport sector, and negative GHG emissions. Each study was conducted using a problem-oriented approach, where the problem at hand dictated the choice of specific methods. The Örtofta CHP plant was used as case study object for data collection. A case study is helpful to obtain a detailed perspective and in understanding the real-life context in which an operator or other actor operates [44]. The data collected included, but were not limited to, Örtofta CHP operations and business strategies. Other data sources utilised included academic literature, official reports and statistics, and grey literature published by energy sector actors.

In this thesis, Technology assessment has been an important approach for assessing sustainability impacts of biobased CHP plants in relation to the overall energy system development. The consequences of different sustainability requirements associated with CHP production must be analysed from a systems perspective to manage conflicts in different objectives. This has for example been determined necessary to get a comprehensive view of trade-offs and potentials of integrating biofuel production with DH systems [45]. Modelling material flows, systems analysis, as well as expert discussions and dialogues with stakeholders, are common methods when assessing potential consequences of energy supply technologies, in relation to sustainability strategies [46,47]. The knowledge is needed when assessing impacts of political goals and measures for sustainability, and consequently, to provide robust policy advice (ibid.).

Potential development pathways for biobased CHP plant technology were assessed through conceptualisation of prospective process chains, and contextualisation through life cycle GHG emission assessments, sensitivity assessments and qualitative discussions. Several methods of life-cycle analysis (LCA) were employed (**Papers II-IV**), which were chosen based on their aim and the research question at hand. A common factor in the LCA methods was that the results would provide relevant decision guidance for an operator in Sweden if the investigated concepts were to be realised. In other words, the results indicate how interesting a particular concept is for the CHP sector regarding life cycle GHG emission performance. The aim of this work was not to identify the most suitable LCA method. Rather, a number of different relevant LCA-based decision-making tools, with their own goals and interpretation of the results, were used. The aim was to reflect reality for the CHP operator. This resulted in a knowledge repository that allows technology to be evaluated from a set of different viewpoints, and to which other decarbonisation technologies may be compared.

2.2.1 Research processes in the papers

The first objective in the first study (**Paper I**), was to thoroughly understand and confirm the connection between the wood fuel fractions entering the Örtofta CHP plant, in this case a mix of untreated[1] wood and waste wood, and the quality of the ash. A mass balance was achieved by analysing the wood fuel fractions used, the mixture entering the boiler, the additives and the resulting ash at the Örtofta CHP plant. The second objective was to seek the energy sector relevance of the resulting connection between wood fuels and ash content. This was met by compiling available statistics of CHP plants using untreated wood and waste wood, as well as statistics on ash produced from wood fuels. Finally, opportunities of, and challenges to, technological and financial solutions, and the current state of the policy environment regarding wood ash recycling and choice of fuel mix, were assessed using a literature study and Kraftringen Energi AB data.

In the second study (**Paper II**), the first objective was to estimate how the amount of heat available would be affected when integrating a pyrolysis reactor into the Örtofta CHP plant, since the issue being studied was the declining demand for residential heating. The work that had recently been done by C Gustavsson [18] allowed for a process chain to be conceptualised using operational data from the Örtofta CHP plant and literature values for pyrolysis. The process modelling tool CHEMCAD, designed and run by co-authors C Gustavsson and P Ottosson,

[1] Untreated wood fuels refer to what is also called primary and secondary biomass residues [62], such as logging residues, discarded round wood, sawdust and bark.

provided the annual demand for wood fuel, internal heat, and electricity, as well as the production of DH, electricity, and bio-oil. The second objective was to assess that the pyrolysis oil produced meets current GHG emission criteria and is comparable to differently sourced bio-oil, so as to be attractive on the biofuel market. It was also important to establish that pyrolysis would not jeopardise the currently low emission factors of the heat and power currently delivered from the Örtofta CHP plant. Therefore, the methodology of the EU RED was used to calculate the GHG emissions associated with the resulting energy outputs. The study thus included the value chain energy and materials from cradle-to-gate. In addition, GHG emissions were calculated using the Alternative Generation Method, which is used by operators in the CHP sector when publishing GHG emissions associated with individual plants, allowing comparisons of environmental performance. Thus, it was important to use this method for the operator perspective.

The study described in **Paper III** was based on the same energy and material inventory as in **Paper II**, but a different approach was employed for the GHG emission calculations. The EU IF methodology was used in this study as it provides decision support for innovative investments in decarbonisation projects. The decarbonisation potential of bio-oil depends on what kind of fuel och product the bio-oil replaces [48]. A process chain was added to include the fuels that would be substituted by the heat, electricity, and refined bio-oil. The bio-oil refinery process was chosen based on a literature study. The study included method evaluation through a sensitivity assessment of the parameters that were identified as those significantly affecting the LCA results.

Kraftringen Energi AB had started to assess the possibility of installing post-combustion carbon capture during the course of the work presented in this thesis. Two add-on technology development concepts, namely pyrolysis integration and BECCS, had been modelled for the Örtofta CHP plant and the results allowed for a comparison of two decarbonisation pathways for a biobased CHP and were presented in **Paper IV**. The LCA methods used in the study were aimed at reflecting the dynamics of decarbonisation of the energy system. This motivated a prospective LCA approach, also based on the experiences from the LCAs in **Paper II** and **III**. Emission factors for electricity, heat, transportation fuels, as well as demand for wood fuels were evaluated to illustrate how different scenarios for decarbonisation influence the life cycle GHG emissions performance of the studied add-on technologies.

3 Towards a circular material chain in biobased CHP plants

3.1 Long-term forest production as a driver for circularity in biobased CHP operations

3.1.1 The role of wood ash in sustainable forestry

Logging residues, which consist of branches and treetops, have traditionally been left in forests after final felling as they are not used in the production of roundwood at sawmills or in the pulp and paper industry. Logging residues are currently used for energy purposes in Sweden, specifically as a solid biofuel for heat and power production (see Figure 1). There is a large untapped sustainable potential in Swedish production forests for harvesting of logging residues for energy purposes [49,50]. However, an excessive outtake of logging residues may lead to a reduction in forest productivity as many nutrients important for forest growth are stored in the tops and branches of the tree.

The nutrients removed from the forest in logging residues are part of the so-called ash-forming materials in the wood. Nitrogen, however, is removed with the flue gas upon combustion. Returning wood ash to the forest is recommended by the Swedish Forest Agency for long-term sustainable logging residue outtake [51]. This practice closes the loop for wood by bringing the ash-forming compounds back to the forest where they can be used as nutrients by new trees. Wood ash also provides a desirable liming effect, which compensates for acidification of the forest soil resulting from logging residue outtake, which would otherwise exacerbate nutrient losses. This practice is in line with the current research consensus on ash recycling to forests as a practice to mitigate negative environmental effects of logging residue outtake [31]. It has also been identified as a commendable practice in other countries in a survey by IEA Bioenergy [52].

The nutrients that are particularly important to recycle are phosphorus, magnesium, potassium and sodium (zinc is also important, however, too high concentrations cause damage). The Swedish Forestry Agency has therefore set minimum concentration limits for these elements to ensure that the wood ash sufficiently counteracts the loss of the above-mentioned elements from logging residue outtake [51]. The recommendations also include upper limits on a number of particularly harmful elements, such as mercury, cadmium, arsenic, lead and copper, to prevent harmful levels of toxic compounds.

3.1.2 The importance of increasing recyclable ash from CHP plants

Swedish forest production models assume that wood ash is recycled back to the forest to the extent recommended by the Swedish Forest Agency to ensure long-term forest production [53]. However, this does not completely compensate for logging residue out-take [51]. The available data indicate that the practice of offsetting the environmental impact of logging residue outtake is not a functioning mechanism, as only a small proportion of the wood ash generated from logging residues is recycled to forest soils, as can be seen in Figure 5.

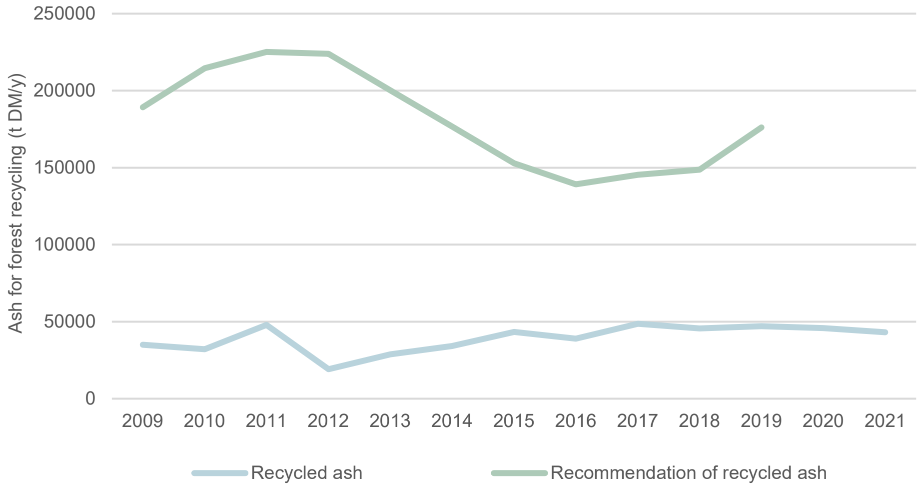

Figure 5. Reported amounts of recycled ash to Swedish forests (t DM/y) [54] and the recommended amount that should be recycled, derived from the 3-year average of logging residue outtake in Sweden and a recommended amount of ash of 3 t DM per ha [51].

Thus, a higher degree of ash recycling is necessary if the high energy potential of logging residues is to be sustainably achieved. The rate of Swedish forest production and outtake has levelled off during recent years [55], in contrast to the prediction of increasing forest production [50]. The trend in forest production is declining, while the outtake continues to increase. This situation underlines the importance of wood ash recycling to ensure long-term sustainable forest production. Since logging residues are primarily used for heat and power production in CHP plants, understanding and facilitating the potential of biobased CHP plants to increase the amount of recyclable ash are of particular importance.

3.1.3 Wood ash production at CHP plants

Different kinds of biofuel require different CHP plant infrastructure (e.g. boiler bed and flue gas cleaning), which in turn influences the quality of the ash produced. There are two prevailing bed types: Fluidised Bed Circulation (FBC) boiler and grate-firing. The Örtofta CHP plant, investigated in the case study in **Paper I,** has an FBC which creates two types of ash. Fly ash is collected from the flue gas, and bottom ash is removed from the boiler bed and contains predominantly used sand. The fly ash is classified as toxic waste due to its high levels of toxic compounds and is disposed of by landfilling. The bottom ash contains the same compounds, but the amount of sand reduces the concentration such that it is not classified as toxic. It is currently used for sealing old landfills. From the perspective of the operator, Kraftringen Energi AB, the large quantities of ash generated at the Örtofta CHP plant sent to landfill constitute a sustainability-related problem, as this conflicts with the environmental circularity goals of the municipally governed owner. No immediate solution to the problem had been found, as landfilling was the sole management strategy offered by the available receivers of the ash. Beyond the environmental issues of landfill, another concern with current fly ash management has emerged for many Swedish CHP plants. The reason is that one of the only large-scale recipients of toxic ash in the Nordic countries, NOAH AS, will soon have filled their landfill site at Langöya [56]. Besides Langöya, there are currently very few alternatives for fly ash from Swedish CHP plants that burn waste products. Ash is not allowed to be stored long-term at the Örtofta CHP plant site, and without another storage site to send the ash, plant operations must ultimately be stopped.

3.2 Co-incineration with waste wood as a potential challenge

3.2.1 Contamination of wood ash by co-incineration

Contaminants such as impregnation chemicals and paint are added to wood during its use, which will prevent it from being recycled [57,58]. This poses a significant problem to achieving the goal of a circular economy [59]. Furthermore, as landfilling with combustible waste in the EU, most waste wood is used for energy purposes [60]. This is in line with the EU Waste Directive and Waste-to-energy communication [61], promoting material recycling and closing material loops. Waste wood, also categorized as tertiary biomass residues [62], is classified according to the contamination level, which in turn depends on its treatments in the use phase. The contaminants are concentrated in the ash, making landfilling the only viable management option for most waste wood ash. There is no political goal in Sweden or the EU to recirculate ash from waste wood to forest soils [63]. The lower price of waste wood than other wood fuels [64], encourage the strategy of co-incinerating solid wood fuels [65], i.e., using a mix of untreated wood and waste wood (the downside being more expensive flue gas cleaning). This leads to the risk of potentially forest-recyclable ash from untreated wood fuels being contaminated by waste wood ash. The fuel used at the Örtofta CHP plant during this study was a mixture of 50% waste wood, 15% logging residues, 25% sawdust and bark, and 10% peat (which has now been phased-out and substituted with increased shares of the other fuels). The wood fuel fractions and ash from the Örtofta CHP plant was analysed to determine the origin of the compounds in the ash (**Paper I**). Figure 6 shows a photo taken during the sampling of wood fuels.

Figure 6 Sample study at Örofta CHP 2018-02-27. Photo: Malin Pettersson.

The results showed that the ash contained too high levels of contaminants to be acceptable for forest soil recycling, and that they originated almost exclusively from waste wood. The results also showed that if the logging residues were to be incinerated alone, the ash would contain sufficient nutrients to meet the current requirements for recycling to the forest. However, all the ash is currently disposed of by landfilling.

3.2.2 Co-incineration as a societal challenge

In **Paper I**, the incidence of co-incinerating waste wood with untreated wood fuels and fate of the wood fuel ashes was studied. One result was that a continued out-take of logging residues and, consequently, a need for compensating forest soils with wood ash would most likely continue over a foreseeable future. This is supported by recent statistics; logging residue out-take for energy purposes has been steady at around 35 PJ/y for the past ten years in Sweden [66], with a turning point in a slightly declining trend in 2021. Between 2013 and 2021, waste wood use for heat and power production increased from 16.5 to 25 PJ/y [67]. An assessment focused on the Swedish DH systems with the highest use of logging residues and waste wood, indicated that co-incineration is widespread and co-incinerating CHP plants are normally large-scale facilities, situated close to coastal areas (**Paper I**). In 2018, the operators of the CHP plant KVV8, Stockholm Exergi AB, applied for an environmental permit to change the fuel mix from untreated wood fuels to co-incineration with waste wood [68]. In fact, two thirds of the national increase in waste wood use between 2018 and 2023 was estimated to be co-incinerated with untreated wood fuels [69].

Available data of the end use of wood ash in Sweden indicated contamination of large amounts of forest fuel ash (**Paper I**). Around 20%, or 40 kt, of the estimated amount of forest-recyclable wood ash produced in 2017 was recycled. Figure 5 shows that the level of wood ash recycling has stayed the same. However, a problem identified in this context is the lack of published data regarding the fate of the ash from heating plants (**Paper I**). The two loops for waste wood and logging residues are schematically illustrated in Figure 7, based on the results in **Paper I**.

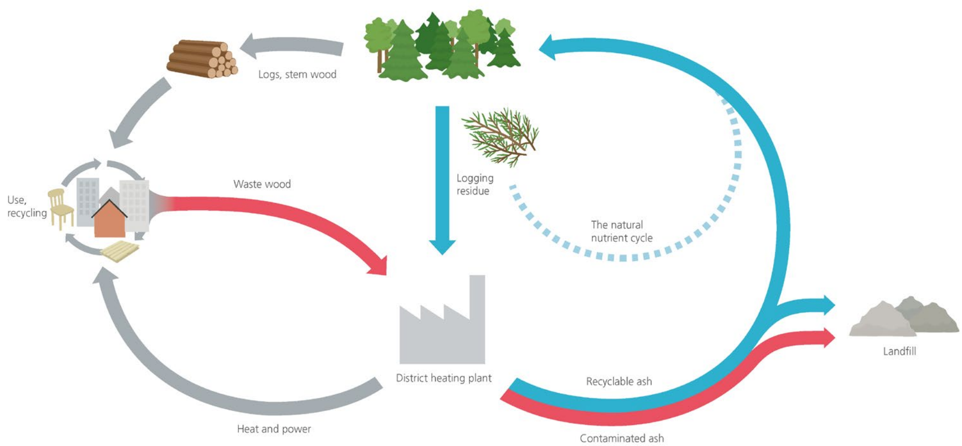

Figure 7. The principal material loops for waste wood and logging residues. Adapted from **Paper I**.

3.3 Opportunities and challenges for increasing recyclable ash from CHP plants

3.3.1 Technical and financial aspects

There are various reasons for designing a CHP plant to operate on a specific mixture of solid biofuels, as done at Örtofta CHP plant. One evident reason is to lower fuel prices, and one is to ensure the security of supply. CHP plant operators thus purchase fuel from various suppliers. For example, the possibility to increase the supply of waste wood in response to demand increases by CHP plant operators is limited, since the supply is dependent on the availability of discarded wood products [70]. The expected cost of the fuel and for the disposal of ash must also be considered and the best fuel mix is determined by a trade-off with the security of supply.

The share of waste wood used at the Örtofta plant has increased continuously since the start of operation due to the lower price compared to logging residues. However, besides the issues of supply security, some technical design parameters limit the possibility to substitute different wood fuels in an existing co-incineration plant. Two such design conditions are limits on the air pollutants in the flue gas, as stipulated in the environmental permit, and the permissible moisture content in the boiler. Too much dry fuel, like waste wood, can generate heat too quickly in just one part of the boiler, which can in worst case damage the boiler [71]. The fuel used affects the flue gas treatment and subsequently the content and properties of the ash. These choices are thus made early in the planning stage before the plant is built. This creates lock-in effects, making it difficult to make major changes in the operational chain of the plant to facilitate other fuel mixes at later stages in the plant's life cycle that do not involve significant investments.

On the other hand, it is technically possible to substitute waste wood in boiler designed to co-incineration with untreated wood fuel, since the equipment requirements are similar [72]. However, it is not financially motivated as waste wood is almost half the price per MWh generated compared to, e.g., logging residues [73]. The results of the analysis of the costs of wood fuel and ash disposal presented in **Paper I** indicate that there is no economic reason to remove the waste wood from the mix to avoid the cost of landfilling. The cost of landfilling is currently too low compared to the increase in cost of using only untreated wood fuels.

An operational strategy to produce more recyclable ash is "seasonal combustion", where the waste wood is used one part of the year, and untreated wood the other part. An obstacle to this strategy for producing more recyclable ash, is that contaminants can linger in the process and contaminate ash from untreated wood fuels [74]. Further, the effect using different fuel streams can result in equipment failure [75].

Chemical and mechanical methods of ash treatment have reached different levels of development [76–81]. However, most methods are aimed at stabilisation and solidification as a step towards disposal by landfilling, rather than recycling [82,83]. Furthermore, ash treatment is expensive [84]. No treatment process has yet been suggested or developed with the aim of removing unwanted compounds, or extracting nutrients that could be used for recycling to forest soil. The increasing interest in secondary mining of valuable materials may lead to the development of better processes aimed at extracting forest nutrients in the future, but this is still mostly focused on recovering rare metals [85].

3.3.2 State of the policy environment

The work presented in **Paper I** showed that the practice of co-incinerating logging residues and waste wood has been overlooked in policies intended to promote a biobased and circular economy, and CHP plant operators thus have no financial or legal reasons to change their current practice regarding ash management. Relevant visions and action plans that could increase the amount of forest-recyclable ash from DH operators exists on different governmental levels, like the EU Circular economy action plan and EU Directive to divert waste from landfills, but no comprehensive political tool or measure. An intention to use more bio-nutrients in the EU has been presented [86], but this has not yet resulted in practical implications for DH operators.

This work presented in **Paper I** also uncovered a goal conflict, as producing more recyclable ash would add to the tariff of biobased DH, and the cost of removing logging residues in general, which could have negative effect of the EU goal of increasing renewable energy. This needs to be addressed by policy makers. In Swedish legislation on forest protection (*Skogsvårdslagen*) it is stipulated that the removal of tops and branches from the forest must be compensated for [51], which can include other products than wood ash. However, according to an administrator at the Swedish Forest Agency [54], the recommendations are difficult to enforce as the ash is produced by CHP plants. Thus, forest owners have no control over the availability of recyclable ash. One possibility could be to require the recycling of ash in the environmental permits of CHP plants using forest fuels. However, such a requirement should not jeopardize the important role of biobased CHP plants in delivering low-carbon-footprint heat and power.

3.4 Key insights

Based on the work presented in detail in **Paper I**, it was found that:

- The contamination of wood ash threatens recycling forest nutrients back to the forest, and thereby long-term forest production.
- Co-incineration waste wood with forest fuel is a favourable fuel strategy, due to fuel price and security of supply.
- If not co-incinerated, the ash from the forest fuels would have fulfilled the recommendations for ash recycling to the forest. Circular & biobased economy goals have overlooked the ash recycling impact of co-incineration.
- There are no economic, political or technical incentives to increase the amount of wood ash from CHP plants to forest soils.
- A comprehensive policy is needed for bioenergy use, which supports forest recycling of wood ash. However, the important role of biobased CHP for low-carbon DH and power should not be compromised.

4 From district heating to liquid biofuels

4.1 Making use of the decline in district heating demand

From the general resource and energy efficiency perspectives, a reduction in the demand for heat is desirable. However, this poses a challenge for CHP plant operators as the amount of electricity generated will also be reduced, since it is a by-product of heat production in Swedish CHP plants, leading to stranded assets [87]. The heating load on Swedish DH grids is expected to decrease in the future due to energy efficiency measures in buildings, climate change, and an increase in the installation of heat pumps [3,27]. A 20% decrease in the total heating demand has been predicted in Sweden by 2050 [23]. The profitability of wood-fuel-based CHP plants is reliant on DH sales and some plants must cease heat production during the summer months when the demand for residential heating is low (ibid.). The length of this down period depends on latitude and whether customers require heat beside space heating. The typical period of operation of a CHP plant supplying heat to a DH grid in Sweden is about 8 months per year [88]. This is also the case for the Örtofta CHP plant. The downtime is usually around 2500 h per year, including six weeks for revision.

In order to meet these changes, and to optimise investments in CHP plants and the associated infrastructure, operators are investigating new and innovative uses of heat. Kraftringen Energi AB has, for example, installed a new steam pipeline from the Örtofta CHP plant to the neighbouring sugar mill. However, this kind of exchange is only possible at CHP plants with heat-demanding industries in their vicinity. Therefore, a more interesting general strategy for the heating sector is to investigate how the CHP plant operators' own product portfolio can be expanded to include heat-demanding processes. The incorporation of a complementary heat-demanding process could offer a means of not only utilizing the overcapacity resulting from falling demand in the DH grid, but also extending the operating season of the CHP plant.

4.2 The need for low-carbon liquid biofuels

Although the heat and power sector in Sweden is largely decarbonised, the transport sector remains a challenge. Domestic transport accounts for almost a third of Sweden's total GHG emissions and is dominated by emissions from road traffic [89]. GHG emissions from domestic transport (Figure 8) decreased by about 21% between 1990 and 2021; the latest emission levels (2021) being about 15 Mt CO_2-eq per year.

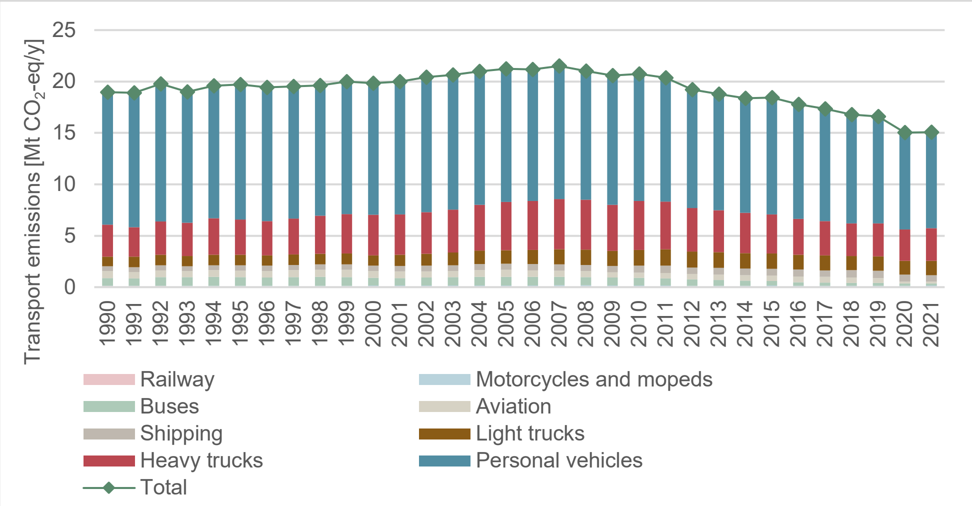

Figure 8. GHG emissions from domestic transport between 1990 and 2021 [89].

The main reason for the decrease is the blending of biofuels in fossil fuels, followed by electrification and energy efficiency measures. All of these have been defined as key measures if we are to achieve the Swedish goal of climate neutrality by 2045 [90,91]. The Swedish Reduction Obligation (*Reduktionsplikten*) has been introduced to increase the production and market share of fuels from domestic, renewable sources, including biobased oil products [92]. Even so, the Swedish domestic transport sector is still largely dominated by fossil fuels, unlike the CHP sector. There is thus an urgent need to produce sustainable alternatives to fossil transportation fuels on a commercial scale, while maintaining the important energy system services provided by the CHP sector. The Swedish Parliament has set the goal of reducing GHG emissions from the Swedish transport sector by 70% by 2030, compared to the 2010 level. The demand for biofuels for transportation in the EU has been predicted to double in the coming decade, from the current value of 7% to 14% of the total transport fuel supply, corresponding to some 1700 PJ/y [26,93]. Until now, the demand for liquid biofuels (Hydrotreated vegetable oils (HVO), Fatty acid methyl esters (FAME), and ethanol) in Sweden has mainly been satisfied by imported oil products, although about 11% (7.9 PJ) of biofuel production was based on domestic feedstock in 2021 [94]. According to current Swedish reduction obligation levels, the demand for bio-jet fuels and HVO in 2030 is expected to be three times as high as the use in 2019 [94]. There is thus an urgent need of large quantities of sustainably produced liquid biofuels to replace fossil fuels.

4.3 A heat-demanding bio-oil process for CHP integration

The transformation of solid biofuels to liquid biofuels at a high energy yield is challenging. Several processes for the conversion of solid to liquid fuels (as either intermediates or end-use products) such as pyrolysis, the Fischer-Tropsch process, gasification and Heat-to-Liquid [95]. Regarding their industrial application, biobased CHP plants and kraft pulp mills have been shown to have the greatest potential for the integrated production of biofuel intermediates, and existing CHP plants with >1 PJ/y of biomass input could produce 42 PJ/y of pyrolysis oil, while CHP plants with >2 PJ/y of biomass could produce up to 15 PJ/y of Fischer-Tropsch crude (ibid.).

Pyrolysis is a chemical process in which lignocellulosic feedstock is converted into a range of smaller carbon compounds, and water, in the presence of heat in an oxygen-poor environment. The products form a char, a liquid, and a gaseous phase. The liquid phase is referred to as bio-oil or pyrolysis oil. Pyrolysis is a heat-consuming process and is thus suitable for integration in a CHP plant, where 60% of the energy content in the wood feedstock can be recovered as a liquid product [96,97].

Bio-oil could also be produced in a stand-alone facility. The advantage of this is that it is independent of the CHP plant operation. However, this has been shown to be less cost, environmental and energy efficient than integration with a CHP plant [18,88,98–100]. The higher energy efficiency is the result of the opportunity to recirculate the by-products from pyrolysis for use as a fuel in the boiler. Furthermore, excess heat from the pyrolysis process can also be recovered. The technical feasibility of producing bio-oil through the retroactive integration of a pyrolysis reactor at the Örtofta CHP plant was investigated, constituting the novel use of both the DH grid and the pyrolysis process as complementary heat sinks (**Paper II**). This would extend the operating season of the plant, increasing its utility and the production of electricity when the demand for DH was low. The resulting net energy yield, between the input of wood fuel and the combined output of heat, power and oil, was shown to be at least 80%. During the summer period when the DH grid could not be used as a heat sink, the yield instead declined to 63-70%.

4.3.1 From feedstock to end use

It is important to assess the energy use and material demand of the entire bio-oil production chain to enable fair and transparent comparisons of resource efficiency and environmental impact with products of equivalent function. In **Paper II** and **III**, sawdust and logging residues were used as pyrolysis feedstocks in two separate scenarios. The choice of feedstock was based on the regional supply potential and suitability for the pyrolysis yields [101].

Bio-oil can be used in stationary combustion facilities to replace fuels such as fossil-based heating oil and vegetable fuel oil fractions (such as mixed fatty acids, MFA), or in dual-fuel (gas/liquid fuel) turbines [102,103]. The feasibility of replacing the MFA used by Kraftringen Energi AB in their peak-load boilers was assessed in a scenario with a small pyrolysis reactor producing 216 or 252 TJ oil per year, using logging residues or sawdust, respectively (**Papers II** and **III**).

The work in **Paper II** and **III** also contained a scenario where the size of the pyrolysis production was maximised, based on the daily allowed number of wood fuel truck deliveries (stipulated in current environmental permit of the Örtofta CHP plant). This resulted in a potential bio-oil production of 2527 (using logging residues) or 2928 TJ (using sawdust) per year, for a potential scenario of selling the bio-oil as transportation fuel. However, untreated bio-oil is acidic, has high oxygen and water contents, and its long-term storage properties are uncertain. The oxygen content may be as high as 40% and must be removed. Distillation is also required for the final products to fulfil the fuel quality requirements for transportation fuels [104]. Hydrodeoxygenation (HDO) in an upgrading process to produce stable hydrocarbons in liquid and gaseous form and was used in **Paper III**. The HDO process uses hydrogen, a catalyst and heat, and produces water as a by-product. No commercial HDO facility exists yet but shows good potential for large-scale refinery implementation. A demonstration scale plant successfully produced gasoline, bio-jet and diesel from pyrolysis-produced bio-oil [105]. Development of an existing refinery process at the Preem Oil Refinery in Lysekil, Sweden, is planned with the aim to upgrade 50 kt pyrolysis oil per year, using hydrogen to remove oxygen, in collaboration with nearby sawmills [106,107].

4.4 LCA for decision-making of decarbonisation technology application

Biofuels are not completely carbon-neutral and can have different GHG footprints depending on various factors, such as the type of biomass feedstock, processing to obtain useful fuel, and transportation to the end user. There are LCA-based decision-marking tools, with different scopes and aims, which can be used to determine the

GHG emissions associated with liquid biofuels. The EU RED includes GHG emission caps for different types of biofuel: aviation fuel, biodiesel, bio-gasoline, biogas, etc., to promote the production of biofuels with low carbon footprints. Heat and electricity are also included in the latest (2nd) revision of the Directive. The Swedish Reduction Obligation is an implementation of the RED into Swedish law, where life-cycle-based criteria on GHG emissions reductions for fuel producers ensure the production of climate efficient fuels. The Alternative Generation Method is methods originally introduced to allocate GHG emissions between DH and power in CHP plants [108]. It is used by the energy company association in Sweden (*Swedenergy*) to monitor and publish the climate impact of Swedish DH grids [109]. The EU IF method is applicable to innovative projects that have the potential to avoid substantial amounts of GHG emissions [110]. GHG Emission avoidance is assessed by comparison with the emissions from a reference scenario, typically business-as-usual, i.e. the emission if the innovative project was not developed.

Paper II presents a detailed LCA on the effects of integrating a pyrolysis reactor at Örtofta CHP plant, including feedstock, additives and transports. This knowledge is important for a CHP operator for deciding on the attractiveness of the potential business case where the bio-oil is sold to an upgrading facility. The climate impact was estimated using the RED methodology and the Alternative generation method. The results in **Paper II** showed that the bio-oil produced would be highly competitive with bio-oils from other processes, from a GHG emission perspective.

The launch of the EU IF in 2021 provides interesting opportunities for funding of innovative climate mitigating projects. The compliance of the studied value chain in **Paper II** with the LCA criteria in the IF is therefore interesting to evaluate for a CHP operator. However, the value chains required to follow the IF LCA methodology differ from those used in the study presented in **Paper II.** The emissions avoidance of a planned project is compared to a reference scenario, which can typically be business-as-usual emissions (i.e., the emissions should the innovative project not be developed). Thus, in **Paper III**, an LCA was performed of a project case in which the bio-oil produced in the study described in **Paper II** was upgraded to provide transportation fuel and substitute for fossil fuels. To provide contextualisation of the choice of parameters and emission factors in the EU IF LCA methodology, sensitivity analysis of the key parameters was performed. The results in **Paper III** showed that liquid biofuel production in CHP plants is a relevant technology for achieving decarbonisation in general, and particularly in the transport sector, in line with the EU IF policy goal.

4.5 Key insights

- Integrated pyrolysis with bio-oil production is technically possible at the Örtofta CHP plant. The existing capacity and infrastructure together with a retrofitted pyrolysis unit could provide an annual production of up to 2.8 PJ (LHV) crude bio-oil (**Paper II**).
- Two wood fuel types, sawdust and logging residues, were identified as feasible feedstock, due to their potential regional availability, and the foreseen future price stability in an anticipated growing forest biomass market (**Paper II**).
- Compared to 2.2 TWh domestic production of liquid biofuels, the Örtofta case could increase the production with 30% (**Paper II**).
- Integrating a pyrolysis reactor with the circulating fluidised bed act as a complementary heat sink to the DH grid and increased the annual boiler uptime of the plant from 5300 to 7752 h. The electricity delivery increased accordingly (**Paper II**).
- The opportunity to offset excess heat from pyrolysis in the DH grid increases the energy efficiency of the pyrolysis process compared to stand-alone operation (**Paper II**).
- The integrated pyrolysis reactor has no significant effects on the already low GHG emissions of the heat from the plant but remains below 1.6 g CO_2-eq/MJ (**Paper II**).
- Integration of pyrolysis would allow CHP operators to diversify their product portfolio and reduce GHG emissions. The Örtofta case study showed a reduction of up to 0.24 Mt CO_2-eq/y compared to the reference case (**Paper III**).
- The bio-oil can be used as transportation fuel to replace fossil fuels, thereby substantially reducing GHG emissions from the transport sector. An estimation showed potential of up to 10.3 Mt CO_2-eq/y in the transport sectors (**Paper III**).

5 Add-on technologies for GHG emission mitigation

5.1 The need for negative emissions

As mentioned in the Introduction chapter, negative emissions are becoming increasingly important if we are to achieve politically set climate goals, such as that in the Paris Agreement from 2015. The role of BECCS is substantial as a mitigation pathway, according to IPCC [21], underlining the important role of mitigating GHG emissions in countries using a high degree of bioenergy in heating plants. It should be noted that CDR does not include methods of avoiding fossil carbon use through substitution with biofuels. The IPCC AR6 report also mentions that substituted GHG emissions from using bioenergy in the heating plant will be of the same magnitude as mitigated GHG emissions using the CDR (ibid.). Thus, from the global perspective, installing biobased CHP plants with carbon capture could be a highly effective GHG mitigation technology, depending on the substituted heat and power sources. The IPCC report also stresses that there are differences in co-benefits, adverse side-effects and mitigation potential (among others) between methods of CDR, which must be considered in implementation strategies.

However, criticism has also been directed at against BECCS. For example, at large-scale deployment, there is a risk that large areas of land would have to be used to grow biomass in order to capture and store carbon dioxide. This would lead to competition with land use for food production and may affect biodiversity conservation or land rights [111]. However, the risks could be the similar for large-scale bioenergy deployment since the feedstock is the same. The risks of adverse effects of BECCS as a method of CDR in the IPCC AR6 technical report do not include the additional CO_2 from redirecting heat and electricity from other uses, or the risk of adverse effects on investments in liquid biofuel production that may arise from promoting CDR.

5.2 CCS in the CHP sector

The amount of research on the application of BECCS to CHP plants has been modest, considering its CDR potential [112]. Yet, Beiron et al [113], estimated the technical potential and associated costs of implementing amine-based CCS in the current biobased CHP plants in Sweden. The results indicated a potential to capture CO_2 from existing biobased and waste incineration plants is 19.3 Mt CO_2/year. However, the delivery of electricity and DH would decrease, depending on the CHP fuel and the heat recovered from the carbon capture process. In general, higher heating recovery rates result in the delivery of more DH and less electricity. Another impediment to the implementation of carbon capture at CHP plants is the high cost of such technology. CHP plants are smaller than other types of CO_2 point-emitting sources (e.g., pulp and paper mills), and are not always operated at full load [16]. Thus, the energy penalty of installing BECCS for individual CHP operators still need to be studied from an energy systems and life cycle perspective. In **Paper IV**, the potential effect on the energy outputs from carbon capture integration at Örtofta CHP was studied.

5.2.1 Emerging carbon capture technologies for the CHP sector

High-energy-consuming carbon capture technologies are not attractive to CHP plant operators as they result is loss of sales [75]. Amine scrubbing using Monoethanolamine (MEA) is a conventional technology used to capture CO_2, e.g., in natural gas and biogas cleaning, but the energy intensity of the process prevents it from being considered an ideal strategy for the large-scale reduction of GHG emissions. However, new carbon capture technologies are being developed, and pilot scale studies are taking place at different CHP plants around Sweden. For example, the energy company Stockholm Exergi AB has received €180 million from the EU IF to install a hot potassium carbonate (HPC) unit at their KVV8 plant [114,115]. The aim is to capture 0.8 Mt of biogenic CO_2 per year at the plant, starting in 2026. An innovative amine-based technology developed by Karlsson et al [116], is being tested in a pilot plant connected to the Sandvik CHP plant in Växjö, southern Sweden, operated by Växjö Energi AB. The amine absorbent is regenerated at a lower temperature than other technologies, and the results regarding the energy demand for the overall capture process are promising. Projects for CCS integration are being planned at other existing Swedish CHP plants including SYSAV in Malmö and Öresundskraft in Helsingborg. Operational starts are planned for 2030 and 2027, respectively [117,118]. **Paper IV** compares the energy outputs from both MEA and HPC capture technologies.

Besides different carbon capture technologies, the integration at the CHP plant can be done using different setups and configurations. For example, Gustavsson et al [119] used a case with the heat and electricity delivery as free parameters. In contrast, if a fix amount of heat should be delivered to the DH, the electricity production will be affected by a lower amount of steam left for the turbine, or electricity being used to run the process. In the Kraftringen Energi AB report that was used as basis for **Paper IV**, the heat output from the plant has been set as a fix parameter, to secure that the DH supply to the Kraftringen Energi AB customers would be unaffected.

5.2.2 Steering measures for BECCS

In the EU, BECCS is regarded as a relevant, complementary tool to other climate mitigation measures. In November 2022, the EU suggested a certification scheme for carbon removals [120], affirming that BECCS is on the European political agenda. In the technical report on which the suggested scheme is based, it is pointed out that CDR technologies, including BECCS, have the potential to affect societal objectives other than climate targets, having both adverse effects and co-benefits, which must be considered when finalizing the certification scheme [121].

There is political support for BECCS in Sweden as well. A Swedish public inquiry, the "Climate policy choices inquiry" (*Klimatpolitiska vägvalsutredningen*), has set a goal for the amount of CO_2 to be captured per year in 2045, which is the year Sweden aims to reach net zero GHG emissions. The ambition is to capture and store 2 Mt CO_2 and 3 to 10 tons per year in 2045 [122]. However, at present, there is currently no market for, or profitability, in BECCS. Rather, companies would incur a cost due to loss of production or increased energy use. As BECCS technology involves long investment cycles and it will take time to build the facilities and infrastructure that must be in place for Sweden to reach the goal of net zero emissions by 2045, government support will be required initially to stimulate development in BECCS [123]. Reversed auctions for negative GHG emissions have been proposed as a steering mechanism to create a market for CCS (ibid.). The first auction is intended to take place during 2023 [124]. The Swedish Energy Agency has proposed a national financial support scheme '*Industriklivet'* to be used to create favourable market conditions for BECCS, and those receiving support holders will also be allowed to participate in the auction scheme (the sales being subtracted from the government support) [125].

5.3 GHG mitigation at CHP plants in the future energy system

5.3.1 Assessing BECCS from a life cycle perspective

Reliable knowledge concerning the prospective life-cycle climate impact is important to ensure effective decision making of policy makers when designing and evaluating steering measures for GHG emission mitigation [126]. Since carbon capture technologies are at the development stage, and the value chain comprises more processes than the actual capture process, it is important to assess the GHG emissions associated with BECCS from a life-cycle perspective. From the perspective of the CHP operator, installing carbon capture technology would involve a high long-term investment and a new business model, as well as new infrastructure and traffic flow to and from the plant. Before making decisions on major investments, it is important that information is available on the effects of integrating the carbon capture technology on the regular heat and power production. Consequences on the electricity and DH delivery of installing CCS at a CHP plant will influence the electricity and DH systems which it is connected to. In turn, the environmental impact of the CHP plant is altered, compared to business-as-usual.

In **Paper IV**, a prospective LCA was performed on a BECCS value chain at Örtofta CHP plant. The conceptualisation and modelling results from an internal study by Kraftringen Energi AB on installing carbon capture were used to assess the life cycle GHG emissions compared to a 2030 reference scenario. The investigated value chain included transportation of the compressed CO_2 from Örtofta CHP, using semi-trailer and ship [127], to Northern Lights injection fields for long-term storage.

5.3.2 Comparison of GHG mitigation by pyrolysis and BECCS

Little attention has been devoted to comparing life-cycle performance of implementing BECCS to other technology development options for CHP plants, such as biorefinery technologies. BECCS can be used to substantially mitigate GHG emissions from the energy system, in a similar way producing biofuels by pyrolysis can mitigate GHG emissions in the transport sector (**Paper III**), [113]. Both BECCS and pyrolysis are technically feasible and close to commercially ready and offer new opportunities to help achieve climate targets in other sectors. Installations in *existing* CHP plants are highly interesting in helping to reach climate goals in a time and resource efficient manner (**Paper III),** [95,128], but the energy they require will affect the energy output of the CHP plant. As mentioned, one of the greatest benefits of biobased CHP production is the low-carbon, energy-efficient delivery of heat and power, and should not be compromised by new infrastructure. Therefore, it is imperative to map out adverse effects and synergies between installing either technology, since both are imminent investments that in worst case creates lock-in effects that hamper investments in the other. Therefore, **Paper IV** included a comparison of the life cycle GHG emissions of integrating a BECCS at Örtofta CHP to integrating pyrolysis and upgrading the bio-oil to transportation fuels. The LCA of the integration of pyrolysis in the value chain in **Paper III** was adapted to facilitate a comparison of the benefits with BECCS. To capture how the LCA results are influenced by the surrounding energy system, different levels of decarbonisation in the 2030 electricity market and transportation fuel market was assumed in the study.

5.3.3 Other CHP plant operator aspects to consider

In the strive to mitigate GHG emissions using biobased CHP plants, other aspects may need to be considered to ensure effective policymaking on implementing GHG mitigation strategies. The aspects mentioned below have emerged during the work with **Paper IV,** and further research on the consequences of them can be valuable.

As mentioned, the profitability of these two mitigation technologies is still uncertain, and both currently involve a loss of revenue in the form of reduced heat and electricity sales. However, grants for both types of projects have been awarded by the EU IF [115], which signals their potential for GHG mitigation, but also underlines their novelty and very high investment costs. The high investment cost could inhibit the willingness or capacity to invest in more than one carbon mitigating technology for the CHP plant. Since the market for negative emissions is under development, but the market for liquid biofuels is already in place, the investments pose different financial risks to an CHP operator, if an investment decision is to be made before profit for the captured CO_2 is established. Further, there are technology and policy instruments for biofuels today but not as developed for CCS (especially not for transport and storage).

CCS operation will also affect the logistical capacity of the plant, which in Örtoftas case could inhibit other climate mitigating technologies that require transportation to and from the plant. For example, CCS integration could risk a successful pyrolysis operation due to space and transport limitations, as pyrolysis would require a large amount of wood fuel trucks and transportation of the oil product from the plant (having bio-oil refinery infrastructure on site would require additional space).

The technological challenges to integrate different kind of carbon capture and pyrolysis differ, which can affect the willingness for the operator to invest. For example, both MEA carbon capture and pyrolysis would require invasive changes to the steam cycle and boiler. HPC technology does not require the same level of integration, as the process can be run on electricity produced outside the steam cycle.

5.4 Key insights

Based on the results in **Paper IV**, the following insights have been prompted:

- Both pyrolysis and BECCS have the potential for significant reductions in GHG emissions as a potential innovative development strategy for CHP plants.
- Integrating pyrolysis generate more electricity when the operational season becomes longer, whilst carbon capture reduces the amount. The energy demand may change with developing carbon capture technologies, such as that of Karlsson and Svensson [116].
- BECCS generate the highest GHG emissions mitigation from a life cycle perspective, around 200 kt CO_2/y. However, they are very much dependent on the development of the surrounding energy system for transportation fuels and other high-value hydrocarbon markets, as well as the electricity system. The results also depend on the scope considered for the emissions associated with those energy parameters, e.g., timeframe, marginal or average mix, and geography.
- Policies that support GHG emissions mitigation should support both pyrolysis and carbon capture technologies for biobased CHP. It is also important that policies take life cycle GHG mitigation potential and the dynamics of the energy system into consideration.
- BECCS is an important for decarbonising the energy system, but counterintuitively, the climate benefit is the highest in an already decarbonised electricity system. On the contrary, the climate benefit of producing liquid biofuels through pyrolysis is lower the more decarbonised the transport sector is.
- The next step is to analyse what strategy to choose as a CHP operator based on the results.

6 Conclusions and outlook

6.1 Conclusions and main contributions

The main contribution of the work presented in this thesis is that it has shown that there are sustainability-related issues of societal importance that interact greatly with the future role of existing wood-fuelled CHP plants. This work has elucidated the opportunities and challenges in CHP production concerning material circularity, changes in heat demand, liquid biofuel production, and carbon capture. A challenge in managing these issues is safe-guarding the role of the Swedish CHP system as a low-carbon, reliable, and dispatchable source of heat and power in the Swedish energy system.

Co-incineration of waste wood and forests fuels is a common practice in Sweden. However, the practice contaminates the ash, which prevents a circular material chain where the ash is used as compensation for logging residue out-take. Technical and economic aspects connected to wood fuel prices, boiler type and ash treatment hamper the willingness of CHP operator to produce more forest-recyclable ash. Further, there are currently no policies that discourage CHP operators from co-incinerating waste wood and forest fuels. In fact, the goal of a circular biobased economy encourages CHP operators to increase their utilisation of waste wood as fuel. Addressing these overlooked challenges are key issues in the transition to a circular bioenergy system.

Integrating bio-oil production by pyrolysis into CHP plants provides a novel heat sink to increase plant uptime and helps CHP operators maximise the utility of plant infrastructure. This is attractive for CHP operators in the light of an expected decline in DH demand. The crude bio-oil would be attractive as a biofuel feedstock according to the EU RED criteria. By upgrading the bio-oil to substitute fossil fuels significant GHG emissions reductions can be achieved, in line with LCA criteria in the EU IF. The work in this thesis indicated that the annual GHG emissions reduction potential from pyrolysis integration in the Swedish CHP sector corresponds to 50–60% of Swedish 2019 transportation emissions. The work demonstrates an opportunity for CHP plant operators to help decarbonise a hard-to-abate sector.

Installing carbon capture technology in biobased CHP plants has potential for significant life cycle GHG emission reductions. However, the mitigation potential of the studied technologies depends heavily on energy systems developments. This was also shown to be the case for pyrolysis integration. The reasons are an increased energy use and a dependency on decarbonisation levels in the transport and electricity sectors. Implementation strategies for GHG emission mitigation methods should consider emissions from a life cycle perspective. A key issue from the life cycle perspective is the decarbonisation development scenarios in the transport and electricity markets.

These opportunities and challenges will be important to address in policymaking and energy systems studies, to optimise the capacity of biobased CHP plants in, and towards, realising a biobased and circular economy.

6.2 Outlook and further research

When **Paper I** was published, there was considerable discussion on the sustainability of peat as a feedstock, but the use of logging residues for heat and power production on the EU level is now also being questioned. Excluding logging residues in the energy sector (at time of writing, a decision is underway) would reduce the security of fuel supply resulting from the use of a wide range of wood fuels. Leaving logging residues in place removes the need to recycle the ash. The CHP operator perspective on sustainable forestry and the impact on wood fuel production is a highly relevant area for further study, as the Swedish heating system is largely dependent on these types of fuel. Changes in the sustainability classifications of wood fuels, for example, in EU legislation, could have critical impact on heat producers' business plans, such as willingness to invest in new wood-fuelled plants. The field of sustainable forestry is complex, and includes, but is not limited to, issues of biodiversity loss, deforestation, soil carbon loss, and carbon cycles – areas that have not been addressed in this thesis but in of great importance to incorporate in research about sustainability of biobased CHP.

Sustainable material management at CHP plants is not restricted to the ash. Once the sustainability of fuels and ash has been assessed, the focus shifts towards other materials, such as additives used in the processes. To ensure sustainable CHP practice, other materials must also be assessed from a circularity perspective.

Efficient use of biomass will continue to be crucial in achieving sustainability in the energy system, and the transition towards a circular, biobased economy in general. The work presented in this thesis has added to the knowledge on the practical measures that can be taken to improve biomass resource efficiency. The future use of forest residues and waste wood must be continuously assessed as refinery technology is developed, and new policies are implemented. The effects of electrification must also be considered.

This thesis focused on a stakeholder in the decarbonised Swedish heating system. The outcome of this thesis highlights that there are relevant opportunities to strengthen the competitiveness of biobased CHP plants through prolonging the operational season and open to new markets, whilst adding to the potential of GHG emissions reduction. A large-scale roll-out of solid biobased CHP plants to substitute fossil-based heating and electricity delivery must also require large investments in new equipment and infrastructure. In regions and countries where a shift towards biobased CHP is a technical option but financially uncompetitive because of low heating demand (including short heating season), pyrolysis could be studied as an option from the planning start, to increase the competitiveness. Further studies into the area would add interesting knowledge about heating decarbonisation opportunities on a global level.

Traditionally, the greatest profit at Swedish CHP plants has been obtained from heat delivery. The steam cycle has therefore been configured to maximise heat delivery at the cost of electricity. This trend has been strengthened by Sweden's historically low electricity prices. As a result, many DH producers have only considered new investments in heat-only boilers, as the production of electricity did not create sufficient profit to warrant investments in turbines. The situation has changed drastically over the past two years. The effects of the war in Ukraine have had serious effects on the European heating and energy market, leading to unprecedented increases in the prices of electricity and gas, including in Sweden, as a part of the European electricity market. This, in turn, has led to the need to move away from electric and gas-based heating. In general, higher electricity prices create a market shift in the energy sector away from heat-only boilers to CHP. Long-term difficulties in the supply of natural gas to Europe may also promote the use of biogas or electrolysis to produce hydrogen for the upgrading of bio-oil. Another development is the increase in intermittent electricity production, predicted to trigger more volatile electricity prices in the future. Therefore, CHP operator strategies into future electricity delivery is also a highly relevant area to study.

Besides the more short-term effect of higher electricity prices, long-term heating development is also prompted in Europe. IEA has stated that "Russia's invasion of Ukraine and related risks to heating energy security and affordability are providing unprecedented momentum for a transition away from fossil fuel-based heating, particularly in Europe" [129]. This development calls for new knowledge on how the demands and opportunities in CHP business models are affected both short-term and long-term. It will also be important to study how the transition momentum could be harnessed in a way that ensures new heating infrastructure being aligned with societal goals of environmental sustainability, energy equity and security. This calls for knowledge on the ways in which the demands and opportunities in CHP business models are affected, in relation to the societal goals of environmental sustainability, energy equity and security.

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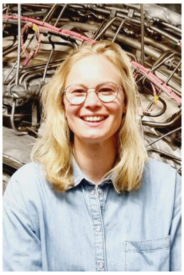
Biobased Combined Heat and Power Production in Sweden



The heating demand in buildings make up one quarter of the global final energy demand and more than 85% is generated from fossil fuels. There is an imminent need to decarbonise space heating. To this end, learning from successful examples is important. Sweden is the country in Europe with the lowest emissions of greenhouse gases from heating. The installation of biobased combined heat and power plants, connected to district heating systems, has been a main driver. New opportunities and challenges to the sustainability of this technology emerge in the transition to a biobased and circular economy. These include circular management of ash, opportunities to develop into biorefineries and produce liquid fuels, and capturing biogenic carbon dioxide, which are all assessed in this thesis. Understanding and disseminating how operators of biobased combined heat and power plants is affected by, and could manage, these sustainability issues will be essential for political steering towards a sustainable energy system whilst safeguarding the current important role in society.

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