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System studies of forest-based biomass gasification

Elisabeth Wetterlund

Division of Energy Systems
Department of Management and Engineering
Linköping University,
SE–581 83, Linköping, Sweden

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SE–581 83, Linköping, Sweden
Tel: +46 13 281000

This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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Abstract

Bioenergy will play an important role in reaching the EU targets for renewable energy. Sweden, with abundant forest resources and a well-established forest industry, has a key position regarding modern biomass use. Biomass gasification (BMG) offers several advantages compared to biomass combustion-based processes, the most prominent being the possibility for downstream conversion to motor fuels (biofuels), and the potential for higher electrical efficiency if used for electricity generation in a biomass integrated gasification combined cycle (BIGCC). BMG-based processes in general have a considerable surplus of heat, which facilitates integration with district heating or industrial processes.

In this thesis integration of large-scale BMG, for biofuel or electricity production, with other parts of the energy system is analysed. Focus is on forest-based biomass, with the analysis including techno-economic aspects as well as considerations regarding effects on global fossil CO_2 emissions. The analysis has been done using two approaches - bottom-up with detailed case studies of BMG integrated with local systems, and top-down with BMG studied on a European scale.

The results show that BMG-based biofuel or electricity production can constitute economically interesting alternatives for integration with district heating or pulp and paper production. However, due to uncertainties concerning future energy market conditions and due to the large capital commitment of investment in BMG technology, forceful economic support policies will be needed if BMG is a desired route for the future energy system, unless oil and electricity prices are high enough to provide sufficient incentives for BMG-based biofuel or electricity production. While BMG-based biofuel production could make integration with either district heating or pulp and paper production economically attractive, BIGCC shows considerably more promise if integrated with pulp and paper production than with district heating.

Bioenergy use is often considered CO_2-neutral, because uptake in growing plants is assumed to fully balance the CO_2 released when the biomass is combusted. As one of the alternatives in this thesis, biomass is viewed as limited. This means that increased use of bioenergy in one part of the energy system limits the amount of biomass available for other applications, thus increasing the CO_2 emissions for those applications. The results show that when such marginal effects of increased biomass use are acknowledged, the CO_2 mitigation potential for BMG-based biofuel production becomes highly uncertain. In fact, most of the BMG-based biofuel cases studied in this thesis would lead to an increase rather than the desired decrease of global CO_2 emissions, when considering biomass as limited.

Sammanfattning

Bioenergi spelar en viktig roll för att nå EU:s mål för förnybar energi. Sverige har med sina goda skogstillgångar och sin väletablerade skogsindustri en nyckelposition vad gäller modern bioenergianvändning. Förgasning av biomassa har flera fördelar jämfört med förbränningsbaserade processer - i synnerhet möjligheten att konvertera lågvärdiga råvaror till exempelvis fordonsdrivmedel. Används gasen istället för elproduktion kan en högre verkningsgrad nås om gasen används i en kombicykel, jämfört med i en konventionell ångturbincykel. De förgasningsbaserade processerna har i allmänhet ett betydande överskott av värme, vilket möjliggör integrering med fjärrvärmesystem eller industriella processer.

I denna avhandling analyseras integrering av storskalig biomassaförgasning för drivmedelseller elproduktion, med andra delar av energisystemet. Skogsbaserad biomassa är i fokus och analysen behandlar såväl teknoekonomiska aspekter, som effekter på globala fossila CO_2-utsläpp. Forskningen har gjorts på två olika systemnivåer - dels i form av detaljerade fallstudier av biomassaförgasning integrerat med lokala svenska system, dels i form av systemstudier på europeisk nivå.

Resultaten visar att förgasningsbaserad biodrivmedels- eller elproduktion kan komma att utgöra ekonomiskt intressanta alternativ för integrering med fjärrvärme eller massa- och papperstillverkning. På grund av osäkerheter i fråga om framtida energimarknadsförhållanden och på grund av de höga kapitalkostnaderna som investering i förgasningsanläggningar innebär, kommer kraftfulla ekonomiska styrmedel krävas om biomassaförgasning är en önskad utvecklingsväg för framtidens energisystem, såvida inte olje- och elpriserna är höga nog att i sig skapa tillräckliga incitament. Medan förgasningsbaserad drivmedelsproduktion kan vara ekonomiskt attraktivt att integrera med såväl fjärrvärme som med massa- och papperstillverkning, framstår förgasningsbaserad elproduktion som betydligt mer lovande vid integrering med massa- och papperstillverkning.

Användning av bioenergi anses ofta vara CO_2-neutralt, eftersom upptaget av CO_2 i växande biomassa antas balansera den CO_2 som frigörs när biomassan förbränns. Som ett av alternativen i denna avhandling ses biomassa som begränsad, vilket innebär att ökad användning av bioenergi i en del av energisystemet begränsar den tillgängliga mängden biomassa för andra användare, vilket leder till ökade CO_2-utsläpp för dessa. Resultaten visar att när hänsyn tas till denna typ av marginella effekter av ökad biomassaanvändning, blir potentialen för minskade globala CO_2-utsläpp med hjälp av förgasningsbaserade tillämpningar mycket osäker. I själva verket skulle de flesta av de förgasningsbaserade drivmedel som studerats i denna avhandling leda till en utsläppsökning, snarare än den önskade minskningen.

List of Papers

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

I. Wetterlund, E., Pettersson, K., Magnusson, M., 2010. Implications of system expansion for the assessment of well-to-wheel CO_2 emissions from biomass-based transportation. International Journal of Energy Research 34(13), 1136-1154.

II. Difs, K., Wetterlund, E., Trygg, L., Söderström, M., 2010. Biomass gasification opportunities in a district heating system. Biomass and Bioenergy 34(5), 637-651.

III. Wetterlund, E., Söderström, M., 2010. Biomass gasification in district heating systems – The effect of economic energy policies. Applied Energy 87(9), 2914-2922.

IV. Wetterlund, E., Pettersson, K., Harvey, S., 2011. Systems analysis of integrating biomass gasification with pulp and paper production – Effects on economic performance, CO_2 emissions and energy use. Energy 36(2), 932-941.

V. Wetterlund, E., Karlsson, M., Harvey, S., 2010. Biomass gasification integrated with a pulp and paper mill – The need for economic policies promoting biofuels. Chemical Engineering Transactions 21, 1207-1212. Also presented at the 13th International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, PRES 2010, Prague, Czech Republic, August 28-September 1, 2010.

VI. Wetterlund, E., Leduc, S., Dotzauer, E., Kindermann, G., 2011. Optimal localisation of biofuel production on a European scale. Submitted to Energy.

VII. Wetterlund, E., Leduc, S., Dotzauer, E., Kindermann, G., 2012. Second generation biofuel potential in Europe. Submitted to Biomass Conversion and Biorefinery. Also presented at the International Symposium on Alcohol Fuels (ISAF XIX) in Verona, Italy, October 10-14, 2011.

Co-author statement is given in Section 1.4.

Publications based on the same work but not included in the thesis

VIII. Flink, M., Pettersson, K., Wetterlund, E., 2007. Comparing new Swedish concepts for production of second generation biofuels – Evaluating CO_2 emissions using a system approach, in: Proceedings of SETAC Europe 14th LCA Case Studies Symposium, Gothenburg, Sweden, December 3-4, 2007. *(Prestudy for Paper I)*

IX. Wetterlund, E., Difs, K., Söderström, M., 2009. Energy policies affecting biomass gasification applications in district heating systems, in: Proceedings of First International Conference on Applied Energy (ICAE09), Hong Kong, January 5-7, 2009. *(Early version of Paper III)*

X. Wetterlund, E., Pettersson, K., Harvey, S., 2009. Integrating biomass gasification with pulp and paper production – Systems analysis of economic performance and CO_2 emissions, in: Proceedings of 22nd International Conference in Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), Foz do Iguaçu, Brazil, August 31-September 3, 2009, pp. 1549-1558. *(Early version of Paper IV)*

XI. Wetterlund, E., 2010. Optimal localization of biofuel production on a European scale. IIASA Interim Report IR-10-020. International Institute for Applied Systems Analysis, Laxenburg, Austria. *(Early version of Paper VI)*

Other publications by the author not included

XII. Fallde, M., Flink, M., Lindfeldt, E., Pettersson, K., Wetterlund, E., 2007. Perspectives on Swedish investments in biofuels (Bakom drivmedelstanken – Perspektiv på svenska biodrivmedelssatsningar). Working paper no. 36, Energy Systems Program, Linköping University, Sweden (in Swedish).

XIII. Trygg, L., Difs, K., Wetterlund, E., Thollander, P., Svensson, I.L., 2009. Optimal district heating systems in symbiosis with industry and society (Optimala fjärrvärmesystem i symbios med industri och samhälle – för ett hållbart energisystem). Report no. 2009:13, Swedish District Heating Association (in Swedish).

XIV. Lundgren, J., Ji, X., . . . , Wetterlund, E., et al., 2010. Development of a regional-economic process integration model for Billerud Karlsborg AB.

XV. Alvfors, P., Arnell, J., . . . , Wetterlund, E., et al., 2010. Research and development challenges for Swedish biofuel actors – three illustrative examples. Centre of Excellence for fossil-free fuels (Svenskt kunskapscentrum för förnybara drivmedel) f3, Gothenburg, Sweden.

XVI. Leduc, S., Wetterlund, E., Dotzauer, E., 2010. Biofuel production in Europe – Potential from lignocellulosic waste. Proceedings of the Third International Symposium on Energy from Biomass and Waste, Venice, Italy, November 8-11, 2010.

Whether outwardly or inwardly, whether in space or time, the farther we penetrate the unknown, the vaster and more marvelous it becomes

Charles A. Lindbergh (1902-1974)
Autobiography of Values

Man small,
why fall?
Skies call,
that's all

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Thesis outline

This thesis consists of two parts. Part 1, the Kappa (introductory chapter to this thesis), gives an introduction to, and a summary of, the seven papers that form the basis of the thesis, while Part 2 contains the appended papers.

Part 1 is structured as follows:

Chapter 1 gives an introduction and describes the aim of the study and the research questions posed, as well as the scope and delimitations. The chapter also describes the research journey conducted and gives an overview of the included papers, as well as a co-author statement.

Chapter 2 aims to give the reader a background and to describe the context in which the papers of this thesis were written.

Chapter 3 serves as an introduction to biomass gasification and gives an overview of past and present biomass gasification projects. The chapter also presents related system studies of biomass gasification.

Chapter 4 describes the studied systems and the biomass gasification applications included in the papers of this thesis.

Chapter 5 presents the methodologies used.

Chapter 6 provides a summary of the results from the papers, including previously unpublished results. The results are presented in themes corresponding to the research questions.

Chapter 7 contains discussion and conclusions, as well as some suggestions for areas of interest for future research.

Nomenclature

Abbreviations

BF	biofuel
BFB	bubbling fluidised bed
BIG/NGCC	biomass integrated gasification and natural gas combined cycle
BIGCC	biomass integrated gasification combined cycle
BIGDME	biomass gasification with dimethyl ether production
BIGGE	biomass integrated gasification gas engine
BLG	black liquor gasification
BMG	biomass gasification
CCS	carbon capture and storage
CEPCI	chemical engineering plant cost index
CFB	circulating fluidised bed
CHP	combined heat and power
DH	district heating
DME	dimethyl ether
ENPAC	Energy Price and Carbon Balance Scenarios (tool)
EU ETS	European Union Emission Trading Scheme
FAME	fatty acid methyl ester
FGHR	flue gas heat recovery
FRAM	future resource adapted pulp mill
FT	Fischer-Tropsch
FTD	Fischer-Tropsch diesel
GHG	greenhouse gases
HOB	heat-only boiler
HRSG	heat recovery steam generator
LCA	life cycle assessment
LHV	lower heating value
MILP	mixed integer linear programming
NGCC	natural gas combined cycle
O&M	operation and maintenance
P&P	pulp and paper
SNG	synthetic natural gas
TTW	tank-to-wheel
WTT	well-to-tank
WTW	well-to-wheel

Chemical symbols

CH_4	methane
C_xH_y	hydrocarbons heavier than CH_4
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
H_2O	water
N_2	nitrogen

Contents

Part 1 – The Kappa

Part 2 – Included papers

Part 1

The Kappa

1

Introduction

This chapter begins with a brief background and introduction to this thesis. Next, the aim of the thesis and the research questions posed are described, as well as the scope and delimitations of the thesis. The chapter ends with a description of the research journey conducted, which includes an overview of the papers and a description of how they are related to each other, as well as a co-author statement.

With the aim of mitigating CO_2 emissions, diversifying the energy supply and reducing dependence on imported fossil fuels, the European Union (EU) has set ambitious targets for a transition to renewable energy. The integrated energy and climate change policy adopted in 2008 defines general targets of 20% greenhouse gas reduction, 20% reduced energy use through increased energy efficiency and a 20% share of renewable energy by 2020 (European Commission, 2008). Increased production and use of bioenergy is promoted as a key to reaching the targets (European Commission, 2005), as biomass can replace fossil fuels in stationary applications, such as heat or electricity production, as well as in the transport sector. In order to explicitly stimulate a shift to renewables in transportation, the European Commission has, in addition to the overall 20% renewable energy target, set a mandatory target of 10% renewable energy in transport by 2020 (European Parliament, 2009a).

Biofuels[1] are presently promoted in the EU through, for example, tax exemptions and blend obligations. To date, those policies have been successful in stimulating the production and use of what are generally termed *first-generation biofuels*, which basically includes biofuels that are commercially available on the market today. However, an increased use of biofuels in transport is not uncomplicated. Considerable uncertainties regarding production costs and CO_2 emission mitigation potential, as well as issues related to competition with food production, have led to an ongoing debate over the benefits of biofuels.

Second-generation biofuels are often mentioned as the solution to many of the issues related to first-generation fuels. In general, second-generation biofuels have lower specific land use requirements than first-generation fuels, and since they are based on non-food feedstocks, such as various types of waste and forest residues, the competition with food production is low. In the Renewable Energy Directive (European Parliament, 2009a), second-generation biofuels are explicitly stated as

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[1] The term *biofuels* is in this thesis used to denote renewable transport fuels.

a prerequisite to reach the 10% target for 2020. In order to reach the 10% goal without significant reliance on import, and without drastic effects in for example agricultural markets, second-generation biofuels would need to constitute around 30% of the total biofuel use, as discussed by for example European Commission (2007) and Fonseca et al. (2010).

Sweden, with its abundant forest resources and well developed forest industry, can be expected to be of key interest for future large-scale production of second-generation biofuels. However, what could easily be seen as a major drawback of second-generation biofuels, is that they do not yet exist on the necessary scale. Today all second-generation biofuel technologies are still at the development or demonstration stage, with high or uncertain production costs. This of course makes estimates of future costs, CO_2 performance and energy efficiency extremely difficult. Due to the disadvantages of biofuels of the first-generation, and the projected advantages of those of the second, hopes are however still high that the development will soon reach the state where biofuels produced from low-grade lignocellulosic feedstocks can be supplied to the market at competitive costs.

In general terms, two basic concepts for production of second-generation biofuels from lignocellulosic feedstocks are usually defined – hydrolysis and fermentation to ethanol, and gasification with downstream synthesis to, for example, Fischer-Tropsch diesel (FTD), methanol or dimethyl ether (DME). While lignocellulosic ethanol benefits from fitting in a to some extent already established market, the gasification process has the advantage of great flexibility on both the feedstock and product side. Biomass gasification (BMG) can also form the basis of electricity production in a combined cycle (biomass integrated gasification combined cycle, BIGCC), in which case it has the advantage of enabling higher electrical efficiency than is possible in conventional combustion-based steam turbine cycles.

Even when considering waste streams from forest or agriculture, for example, biomass is still a limited resource, which makes efficient utilisation essential. BMG-based processes have a considerable surplus of heat that, if left unutilised, lowers the overall process efficiency. Integration of BMG processes with heat sinks of different kinds, or co-production of several energy carriers, gives an opportunity for higher total conversion efficiencies. Potential integration locations could for example be district heating (DH) systems or industrial processes. Since the processes will likely need to be very large to reach necessary efficiencies and economies of scale, as discussed for example by Faaij (2006) and Edwards et al. (2008), significant demands are placed on the choice of location, as well as on the biomass supply chain. Even though the BMG processes are not yet ready to be realised at full scale, it is important to already begin conducting system studies of how in the future they can be implemented in the larger energy system.

This thesis employs a systems perspective to investigate the integration of BMG-based processes utilising forest biomass as feedstock, with other parts of the energy system. The analysis includes techno-economic aspects, as well as considerations regarding effects on global CO_2 emissions.

1.1 Aim and research questions

The aim of this thesis is to analyse how technology for biomass gasification, for biofuel or electricity production, from forest biomass, can be integrated with other parts of the energy system, and what consequences this kind of integration may have. Further, this thesis aims to investigate key parameters affecting investments in biomass gasification, in particular regarding energy market conditions and policy instruments. The thesis is focused around the following research questions:

1. Can investment in large-scale biomass gasification technology be an economically attractive option for integration with ...
    (a) ... district heating?
    (b) ... pulp and paper production?
2. What levels of economic policy support are needed to make investments in biomass gasification technology economically attractive?
3. What could be suitable locations for future large-scale biomass gasification plants?
4. How would implementation of large-scale biomass gasification technology affect global fossil CO_2 emissions?

Research question 1a is addressed in Papers II-IV and VI. Paper VII includes the possibility to integrate biomass gasification with district heating, but does not explicitly discuss this aspect. *Research question 1b* is addressed in Papers IV-V. The issue of policy support (*research question 2*) is covered in Papers III, V and VII, and to some extent also in Paper VI. *Research question 3* is connected to research question 1, but with a widening of the perspective. Paper VI is the main paper covering question 3, with the discussion also encompassing results from Papers II and IV. *Research question 4* is addressed in all papers except Papers III and V.

Table 1 gives a summary of which research questions are considered in each of the appended papers.

Table 1: Research questions in each of the appended papers.

Research	Paper						
question	I	II	III	IV	V	VI	VII
1a		•	•	•		•	(•)
1b				•	•		
2			•		•	(•)	•
3		•		•		•	
4	•	•		•		•	•

1.2 Scope and delimitations

The scope of this thesis is system studies of applications for gasification of solid biomass. The focus is on advanced large-scale applications for production of biofuels and/or electricity. One of the papers (II) also considered BMG applications on a smaller scale, which are not explicitly discussed in Part 1 of this thesis. Three of the papers (I, VI and VII) included biofuel production technologies not based on BMG[2]. Those technologies are only briefly touched upon in the following chapters.

Even though two of the three systems studied in this thesis are local Swedish cases, the systems analysis is done with a European energy systems perspective. The focus is primarily on forest-based biomass. Agricultural biomass feedstocks or waste resources other than forest residues, have not been considered. The time frame considered is mainly the medium-term future (2020-2030).

1.3 Terminology and definitions

The term *biofuel* is used to denote renewable transport fuels. *Biomass* and *bioenergy* denotes matter of biological origin, which can be used either directly, or after conversion into other energy carriers. *Biomass gasification (BMG)* is used for thermochemical gasification of solid biomass, while biochemical gasification is denoted *anaerobic digestion*. The term *biogas* is used for the methane-rich gas produced via anaerobic digestion, and *synthetic natural gas (SNG)* for methane derived from *syngas* or *synthesis gas*, which in turn is the upgraded product gas from thermochemical gasification. *Biodiesel* is used for fatty acid methyl ester (FAME) products, while *synthetic diesel* or *Fischer-Tropsch diesel (FTD)* is used to denote diesel products from syngas. The term *biorefinery* is used for multiple output bioenergy conversion facilities other than combined heat and power (CHP) plants.

1.4 Paper overview and research journey

In this section, each of the appended papers is described, as is the context in which they were written, with my contribution described for each paper.

Paper I

The first year of my PhD studies was mainly spent participating in courses within the interdisciplinary post-graduate school the Energy Systems Programme. The grand finale of the course year was a large interdisciplinary project (Fallde et al., 2007), from which the idea for Paper I was born.

In Paper I, I worked in close co-operation with Karin Pettersson, Chalmers and Mimmi Magnusson, KTH. We investigated the effects of expanding the system, when evaluating well-to-wheel (WTW) CO_2 emissions for biomass-based transportation alternatives, to also include the systems surrounding the studied biomass

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[2] DME via black liquor gasification (BLG), and lignocellulosic ethanol.

conversion system. The results showed that when expanding the system, it is not certain that biomass-based transportation leads to decreased CO_2 emissions.

Paper I was a joint effort by me, Pettersson and Magnusson. I was responsible for the input data and calculations related to BMG, Pettersson for the black liquor gasification input data and calculations, and Magnusson for the ethanol input data and calculations. The planning of the paper, analysis and writing was done by all three authors in collaboration. Associate Professor Mats Söderström, Professor Simon Harvey and Professor Per Alvfors supervised the work.

Papers II-III

After the course year, I set out on the part of my research journey where I performed case studies of different BMG integration alternatives. In the first part of this, I co-operated with my fellow PhD student Kristina Difs in a study of possibilities to introduce BMG in a DH system, using Linköping as a case.

Paper II aimed at performing a broader screening of the performance of various BMG applications in DH systems. The results showed that BMG can be economically profitable for the DH supplier, and increases the potential for production of high-value products (electricity or biofuel) as well as for decreased CO_2 emissions. However, the results were shown to be dependent on the assumed energy market conditions, in particular with regard to policy support for renewable energy.

Paper III is a continuation of the work in Paper II, with the aim to evaluate how much policy support would be needed to make investment in BMG profitable in the DH system, under varying boundary conditions. The results showed that significant support would be needed to make BMG-based biofuel production competitive with biomass-based electricity generation, while BMG-based electricity production can be competitive with conventional steam cycle technology even without policy support, given sufficiently high electricity prices.

In Paper II, Difs and I shared the work equally, with me providing the idea and general outline for the study. Difs was responsible for the DH system input data, while I was responsible for the BMG parts. I did most of the modelling work and model runs, with co-operation by Difs. The study design, analysis and paper writing were done by me and Difs in collaboration. Associate Professor Mats Söderström and Associate Professor Louise Trygg supervised the work. Paper III was planned, performed and written by me, and supervised by Söderström.

Papers IV-V

In the next part on my research journey I moved from a local energy system focus to an industrial focus. In a conference paper not included in this thesis (Wetterlund et al., 2009), I co-operated with Karin Pettersson, Chalmers, with the aim of studying BMG integrated with a pulp and paper mill. As a case we used a model kraftliner mill from the FRAM project (Delin et al., 2005). During this period of time, I got involved in a research project involving the Billerud Karlsborg pulp and paper mill outside Kalix in northern Sweden. Within the frame of this project, I remade and developed the calculations and analysis from the conference paper, for the Billerud mill. This led to the writing and publication of Paper IV, the aim of which was to analyse the system effects of integrating BMG with pulp and paper production. The results showed that BMG could be profitable for the mill, under certain energy market conditions. However, the dependency on policy support for biofuels and renewable electricity was again shown to be strong.

For Paper V the aim was to further investigate the level of economic policy support for biofuels needed to make investment in DME production profitable for the pulp and paper mill. The results showed that the required support is strongly connected to the price ratio of oil to biomass, and highly sensitive to changes of the required capital cost.

I provided the original idea and general outline for the study in the conference paper, with the detailed planning done by me and Pettersson together. Pettersson had the main responsibility for the integration calculations. For Paper IV, I did most of the planning, as well as most of the integration calculations. The analysis and writing was made primarily by me, with assistance by Pettersson. Paper V was planned, performed and written by me. Professor Simon Harvey and Associate Professor Mats Söderström supervised the work in both papers, and Associate Professor Magnus Karlsson supervised the work in Paper V.

Papers VI-VII

During my final year as a PhD student I participated in the Young Scientists Summer Program (YSSP) at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. In my project I worked with a techno-economic, geographically explicit model that can be used to analyse bioenergy conversion options. My task was to develop and run the model on the European level, which I did in close co-operation with Dr. Sylvain Leduc, IIASA. For this, I used knowledge and input data emanating from the studies in Papers I-V.

At the end of the YSSP period, the work was published as an IIASA report (Wetterlund, 2010). Paper VI is based on this report, but with new model runs and new analysis. The overall aim of the paper was to present the model development and use, and to determine and investigate advantageous locations for production of second-generation biofuels. The results showed that a significant share of the total transport fuel demand in the EU can be met by second-generation biofuels, given sufficient policy support for biofuels or a sufficiently high cost for emitting CO_2. Paper VII is a continuation of the work in Paper VI, with more focus on how the biofuel production is affected by policy instruments and fossil fuel prices.

Papers VI-VII were planned, performed and written jointly with Leduc. Leduc did the main part of the modelling work on the optimisation model, while I provided and updated the input data. I also contributed to model development and model validation, as well as performed most of the model runs. Dr. Georg Kindermann was responsible for the modelling of forest biomass supply and Adjunct Professor Erik Dotzauer provided comments and discussion.

2

Background

This chapter describes the context in which the papers of this thesis have been written, and gives a brief introduction to biomass resource issues, biofuels, and relevant policies and policy instruments.

2.1 Biomass resources

Biomass is "material of biological origin excluding material embedded in geological formations and transformed to fossil", as defined in the "Unified Bioenergy Terminology" by FAO (2004). Bioenergy sources can be classified in different ways, for example by origin, or by different characteristics and properties. In a broad sense, biomass can be divided into:

- Woody biomass, including forestry by-products from logging and thinning, plantation wood, forest industry by-products such as black liquor, and recovered waste wood.
- Herbaceous biomass, including energy grass and agricultural residues such as straw.
- Biomass from fruits and seeds, including agricultural primary products in the form of oil seeds and grain crops.
- Organic waste, for example from households, the food-processing industry and slaughterhouses, as well as in the form of sewage sludge.

As has been mentioned, this thesis focuses on woody biomass originating from the forest.

Today biomass provides about 10% of the global energy supply, amounting to around 14 PWh per year, of which the main part (over 80%) originates from wood or shrubs, in the form of trees, branches and residues (Chum et al., 2011; IEA, 2011a). However, most of this is in the form of low-efficiency traditional biomass use[3], with only slightly more than a fifth being in the form of high-efficiency modern bioenergy use, such as generation of electricity, heat, combined heat and power (CHP) or transport fuels. On a European level the use of bioenergy amounted to just over 1.2 PWh in 2009, which was about 6% of the total energy use (Eurostat,

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[3] Biomass consumption for cooking, lighting and space heating in the residential sector in developing countries. Often entails unsustainable use of biomass resources.

2011). As comparison, Sweden, being a country with large biomass resources, has an approximate 20% bioenergy share, or around 120 TWh per year[4] (SEA, 2010).

When estimating the future availability of biomass for energy, it is important to clearly define the type of potential being discussed. The boundaries of the different potentials are not consensually defined, but in general four types of potential can be distinguished (see e.g. Torén et al. (2011)). The *theoretical potential* is the highest level of potential, which only takes into account fundamental bio-physical limits. The *technical potential* takes into account spatial restrictions, such as other land uses (for example food, feed and fibre production, as well as land set aside as natural reserves), as well as technical limitations regarding for example harvesting techniques, infrastructure, accessibility and conversion efficiencies. The *economic potential* is the share of the technical potential which can be fulfilled at cost levels considered competitive. Finally, the *implementation potential* also takes into consideration socio-political framework conditions, including economic, institutional and social constraints and policy incentives. Implementation potential can also include sustainability criteria.

Concerning the future bioenergy potential, various estimates show a remarkably wide range, also for the same type of potential defined. In a much cited review by Berndes et al. (2003), the possible global contribution of bioenergy was found to range from under 30 to over 100 PWh per year around 2050. In a related study by the same group, Hoogwijk et al. (2003), energy crops were found to have an even larger potential contribution (almost 300 PWh), but also a very large variance. In more recent studies, Dornburg et al. (2010) narrowed the range down to 50-140 PWh per year in 2050, when considering for example water limitations, biodiversity protection and food demand, while Haberl et al. (2010) estimated the potential at 40-80 PWh per year, if sustainability criteria are considered. The IPCC SRREN Bioenergy report (Chum et al., 2011) concluded from their review of the available scientific estimates, that deployment levels of biomass for energy could reach 30-80 PWh per year in 2050. In the report the point was also stressed however that it is impossible to narrow down the technical biomass potential to precise numbers, due to the large inherent uncertainty of a number of factors. Factors having large influence include population development, as well as economic and technological development, and how these translate into fibre, fodder and food demand, development in agriculture and forestry, climate change impacts on future land use including its adaptation capability, and consequences of land degradation and water scarcity.

On a European level, the future biomass potential is equally uncertain. For example, the annual bioenergy potential in 2030 was estimated by EEA (2006) at around 3.4 PWh, and by Ericsson and Nilsson (2006) at around 4.8 PWh. In an overview of reported European potentials, made within the Biomass Energy Europe project (Torén et al., 2011), the estimates of biomass potential for 2030 were found to range from 2 to 7 PWh per year, increasing to 5-9 PWh per year for 2050. For Sweden, the Commission on Oil Independence (2006) estimated almost a potential

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[4] Of this about half is industrial use, including black liquor in the pulp and paper industry.

doubling of the biomass use, to 230 TWh, for the year 2050. In a recent report by IVL on how to make the Swedish energy system close to 100% renewable, a slightly more cautious estimate is made, amounting to around 140 TWh bioenergy in 2050 (Gustafsson et al., 2011).

For Sweden, a large share of the total bioenergy used originates in the forest. On a larger scale (global or European) forest biomass however is only of lesser significance, with biomass resources of agricultural origin making up the major share of the future potential.

2.2 Biofuels

First-generation, or conventional, biofuels are biofuels that are available on the market today. The dominant first-generation biofuels are ethanol from sugar or starch crops, and biodiesel from esterified vegetable oil, for example rape seed oil, palm oil or soybean oil. Biogas from anaerobically digested biological matter, such as sewage sludge or various types of wet waste, is also commercially available, and thus counts as a first-generation fuel. Second-generation, or advanced, biofuels, are based on lignocellulosic feedstocks, such as forest residues, different types of waste, black liquor or farmed wood. On the product side, main second-generation biofuel candidates are methanol, DME, SNG and FTD via gasification, and lignocellulosic ethanol. Even though second-generation biofuels have yet to leave the development stage and reach the market, there are already discussions regarding third- and even fourth-generation biofuels. Included in those categories could for example be biofuels from algae, and hydrogen from various renewable resources.

As mentioned in the introduction, the European Commission has set a mandatory target of 10% renewable energy in transport by 2020, with a transitional target of 5.75% for 2010 (European Parliament, 2009a, 2003a). Today the total annual energy use in road transport is approximately 3.6 PWh (European Commission, 2010). Of this less than 4.7% consists of renewable energy (EurObserv'ER, 2010), which is well short of even the 2010 goal. Sweden is one of only seven member states to have reached the 5.75% mark. Figure 1 shows how the shares of biofuels in transport in the EU and in Sweden have developed over the last years. As can be seen, biodiesel is the dominant fuel on a European scale, while ethanol is more prominent in Sweden. Biogas from anaerobically digested waste sources is also mainly used in Sweden.

The last few years have seen increased criticism especially of first-generation biofuels due to issues related mainly to competition with food production and potential negative environmental impact from biofuel production, in particular associated with effects from land use change (Fargione et al., 2008; Searchinger et al., 2008). Although one of the main drivers for a transition to biofuels is reduction of fossil CO_2 emissions, in particular first-generation biofuels do not necessarily contribute to CO_2 mitigation. A number of studies have been made of first-generation biofuels, and the results regarding possible greenhouse gas (GHG) emissions reduction are far from unanimous (see e.g. Larson (2006); Delucchi (2006)).

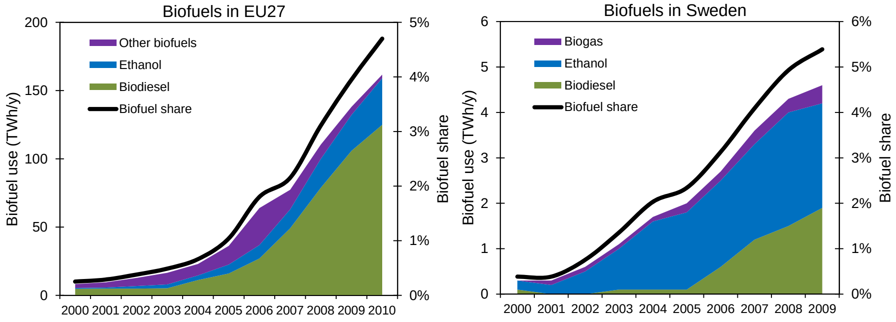

Figure 1: Total biofuel use and biofuel share of total energy demand in road transport (EurObserv'ER, 2010; SEA, 2010; Eurostat, 2011).

2.3 Related policy instruments

The primary objective of energy taxes in Sweden originally was to contribute to state finances. Since the beginning of the 1990s the purpose has shifted, and now the energy taxes also aim to contribute to more efficient energy use, and to decrease the environmental impact from energy use. The main components of the taxation are the energy tax and the CO_2 tax[5]. Heat, electricity and CHP production are taxed differently, with tax reductions for heat production in CHP plants, as well as in industrial facilities. Electricity production is not taxed, while electricity use is. For more information, see Swedish Parliament (1994) and SEA (2010).

The EU Emission Trading Scheme (EU ETS) is a key component of the EU climate policy (European Parliament, 2003b, 2009b). The system has been in place since 2005, with the objective of reducing the GHG emissions in a cost-efficient way, since the EU ETS will promote the measures with the lowest mitigation cost. The EU ETS is a cap and trade system, which means that there is a limit on the total amount of CO_2 that can be emitted. Up to that limit, emission allowances can be traded. The EU ETS currently comprises the energy intensive industry, and electricity and heat producers, covering about 40% of total EU CO_2 emissions (SEA, 2010). Starting in 2012, air traffic will also be included in the system, with even more sectors being added in 2013. The price of emission allowances has varied radically since its introduction, from next to nothing, to over 30 EUR/t_{CO2}, with a price of around 15 EUR/t_{CO2} during the last few years (ICE-ECX, 2011). Ideally, the cost of emitting CO_2 should compensate for the actual marginal costs attributed to CO_2 emissions. Since estimates of these costs are highly dependent on a number of factors, for example discount rate, considered time horizon, and data reporting using mean or median values, the cost range reported in the literature is however very large. Tol (2008), for example, analysed over 200 different estimates. The results showed a median value of 4-20 EUR/t_{CO2}, a mean value of 24-35 EUR/t_{CO2}, and a 95 percentile of 101-163 EUR/t_{CO2}, depending on statistical method used.

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[5] There is also a sulphur tax and a NO_2 fee, where the latter is state financially neutral.

Renewable electricity is currently promoted by policy instruments in all EU member states. The types of instruments differ, with most states applying feed-in tariffs. A number of states apply a green certificate system, a premium or tax exemptions, and a few states also apply a quota obligation in combination with other instruments. Figure 2 summarises current policy instruments and approximate levels of support in the EU member states[6].

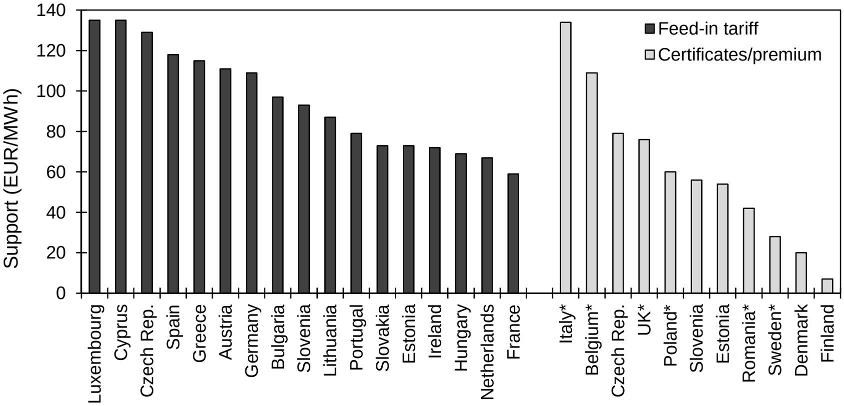

*Figure 2: Overview of subsidy levels for biomass-based electricity production in the EU (2009). The figure includes both feed-in tariff levels, and certificate levels, which are added to the electricity price. Countries marked with * also apply quota obligations (Canton and Johannesson Lindén, 2011; European Commission, 2011).*

In Sweden renewable electricity production is promoted through a market-based system with tradable green certificates. The system was introduced in 2003 and will be effective through 2035 (Swedish Parliament, 2003; SEA, 2010). Electricity producers receive one certificate per MWh produced electricity from approved renewable sources[7]. The certificates are traded between the suppliers and consumers. A quota obligation for consumers creates a demand for the certificates and thus provides them with an economic value. The quota varies during the certificate system time, to gradually increase the demand for certificates. New renewable electricity suppliers receive certificates for the first 15 years of operation. Biomass-based electricity makes up the largest part (over 60%) of the total renewable electricity production entitled to certificates, with a production increase from 4.2 to 9.8 TWh since the start of the certificate system (SEA, 2010). The certificate price has fluctuated over the period, from around 15 to over 35 EUR/MWh. Today the prices are around 20 EUR/MWh (Svensk Kraftmäkling, 2011).

For biofuels there is a great challenge for policy makers to develop and implement efficient policy tools for the future. To be effective a policy must be able to

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[6] Some member states apply more than one type of policy instrument. The figure should be seen as an approximate screening of current levels.

[7] Wind energy, solar energy, geothermal energy, wave energy, certain types of bioenergy, and certain types of hydropower.

create long-term stable conditions for producers as well as users, and preferably not be too burdensome on the governmental budget. Today all EU member states apply some policy measures to promote biofuels. The two most common support measures are tax exemption and quota obligations, or a combination of the two. Tax exemptions have proven effective in the early stages of market development. However, they are costly in terms of loss of fiscal revenues and, if the tax reduction is high, entail a risk for over-compensation. The effectiveness is also very much dependent on the initial excise tax levels. Quota obligations do not burden the public budget, but instead entail higher prices for the end consumers, and can be suitable also for more mature markets. They favour low blends, which means that additional measures, such as subsidies on either the production or the consumption side, may be needed in order to stimulate technology development. Figure 3 summarises current approximate tax exemption levels in the EU member states. For further discussion on the pros and cons of different biofuel policy instruments, see for example European Commission (2009), Wiesenthal et al. (2009) or Hansson et al. (2008).

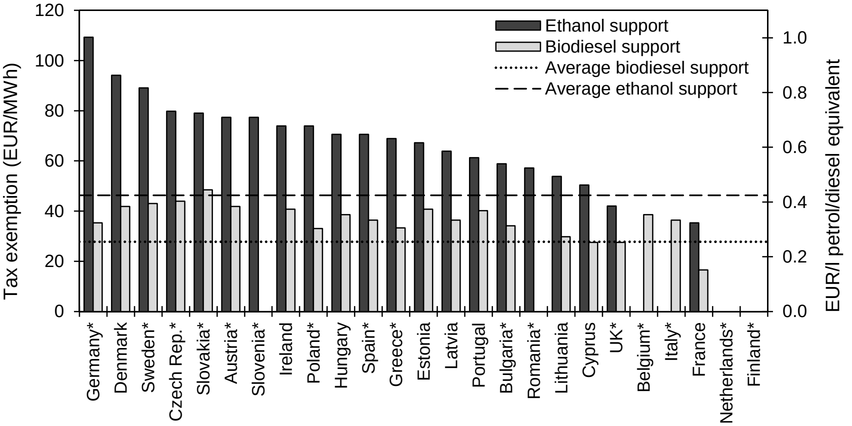

*Figure 3: Overview of tax exemption levels for biofuels in the EU (2008). The figure also shows the average support for ethanol and biodiesel, respectively. Countries marked with * also apply mandatory biofuel quotas (Jung et al., 2010).*

The total subsidies for biofuels in the EU today amount to approximately 3000 MEUR (2008) (Jung et al., 2010; Charles and Wooders, 2011), with the subsidies on a global scale amounting to around 15,000 MEUR (2010) (IEA, 2011b). This can be compared to the corresponding global subsidies for fossil oil, of more than 135,000 MEUR[8]. A phasing-out of fossil fuel subsidies would reduce growth in global energy demand as well as in global CO_2 emissions, and could stimulate the competitiveness of biofuels (IEA, 2011b).

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[8] The largest part of these subsidies are implemented in oil producing, non-OECD countries.

3

Biomass gasification

This chapter gives an introduction to biomass gasification, describing different concepts and technologies for each of the steps in the conversion chain from biomass feedstock to end product. An overview of previous and ongoing biomass gasification projects, and a comment on the commercial status of different technologies, is also given. This chapter also presents related system studies of biomass gasification.

Gasification is thermochemical or biochemical conversion of carbonaceous material into an energy-rich gas. While gasification is commercially available for a variety of fossil feedstocks, gasification of biomass feedstocks for advanced applications is still in the development stage.

In this thesis the term “biomass gasification” (BMG), in accordance with common practice, refers only to thermochemical conversion of solid biomass into gas, unless otherwise explicitly stated. Black liquor gasification (BLG) is a special case of biomass gasification, applicable only for chemical pulp mills. BLG was only included in Paper I of this thesis. It will not be further described here, but many of the process steps described in this section also apply to BLG. For more detailed descriptions and discussions regarding BLG with biofuel or electricity production, see Pettersson (2011).

3.1 Biomass gasification process chain

Figure 4 gives a general overview of BMG-based conversion chains from feedstock to final products. The following sections describe the different process steps included.

3.1.1 Pretreatment

One of the main advantages being emphasised about BMG is the high versatility on the feedstock side, with for example various waste flows from forestry, agriculture and households as possible feedstocks. Depending on the type of feedstock and gasifier, the biomass needs to undergo pretreatment before the gasification. The simplest form of pretreatment is chipping to suitable size, and drying. For certain types of gasification reactors, however, a much finer particle size or even a slurry is needed. The achievement of this is considerably more difficult with biomass materials than with coal, due to the fibrous character and large heterogeneity of biomass.

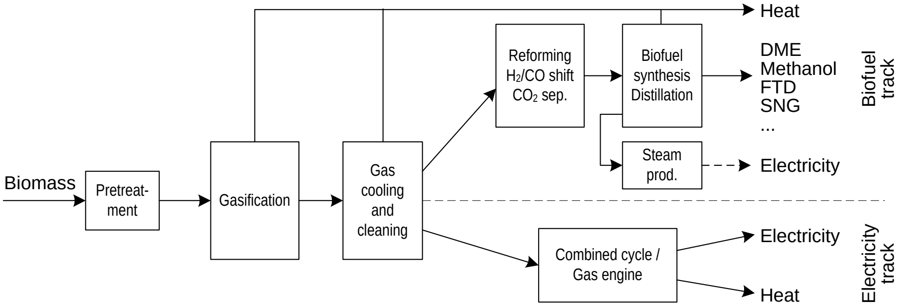

Figure 4: Schematic overview of biomass gasification conversion chains. Note that some steps are optional for certain chains.

Potential pretreatment methods for biomass include grinding to powder or thermal pretreatment. Two suggested thermal pretreatment methods are fast pyrolysis and torrefaction. In fast pyrolysis the biomass is decomposed into a mix of liquid (bio-oil) and solid (char) products in the absence of oxygen, at a reaction temperature of around 500°C (Bridgwater et al., 1999; Bridgwater, 2011). The oil can be used as is, or as a slurry if the char is powderised and mixed with the oil. Torrefaction or slow pyrolysis also takes place in the absence of oxygen, but at a lower temperature of 200-300°C. The treatment destroys the fibrous structure of the biomass and increases the energy density and grindability (van der Stelt et al., 2011). These pretreatment methods have so far only been tested on a small scale, and not integrated with entire BMG chains.

3.1.2 Gasification and gas cleaning

During the gasification process biomass is broken down completely into a combustible gas (synthesis gas or syngas). The composition of the syngas is dependent on the type of gasifier and the operation conditions, the most important being gasifying agent, temperature and pressure, but in general terms the syngas consists of a mixture of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), water (H_2O), heavier hydrocarbons (C_xH_y), and, if the gasifier is air-blown, nitrogen (N_2). For detailed descriptions, see for example Knoef (2005).

Syngas quality can roughly be categorised into low-value gas (4-6 MJ/Nm^3) and medium-value gas (10-20 MJ/Nm^3) (Belgiorno et al., 2003; McKendry, 2002). Low-value gas is produced when air is used as gasifying agent, as the syngas is diluted with large volumes of N_2, and can be used directly as a fuel gas, or for electricity production in gas engines or in combined cycles (BIGCC).

If the purpose of the gasification is to upgrade the gas, for example into biofuels, gas of higher quality is needed. For this, two basic solutions exist – direct (autothermal) gasification using oxygen or a mix of oxygen and steam as gasifying agent, and steam-blown indirect (allothermal) gasification. Direct gasification means that the heat needed to gasify the biomass is produced by combustion of part of the biomass in the gasifier.

There are a number of different types of gasification reactors. Fixed-bed gasifiers are simple and robust, but have limited up-scaling potential and are thus only suitable for smaller applications, up to around 6 MW of biomass capacity (see e.g. Knoef, 2005). In fluidised bed gasifiers the bed, consisting of a granular material like sand, is agitated by the gasifying agent. In bubbling fluidised bed (BFB) gasifiers, the bed is floating but stays in the reactor, while in a circulating fluidised bed (CFB) the bed material is carried out from the reactor to be recovered in a cyclone and transported back to the gasifier. Both types of gasifiers are well suited for scale-up to large-scale applications (see e.g. Knoef, 2005; Olofsson et al., 2005). In indirect gasification the combustion takes place outside the gasifier and the gasification heat is supplied via heat exchangers or circulating bed material. Entrained-flow gasifiers operate at higher temperatures (>1200°C, compared to <1000°C for fluidised bed gasifiers) and produce a very high quality syngas. However, they put higher demands on the feedstock pretreatment, which adds complexity. Figure 5 shows examples of two gasifiers suitable for large-scale gasification of solid biomass with subsequent upgrading to biofuels – one autothermal CFB gasifier and one indirectly heated gasifier.

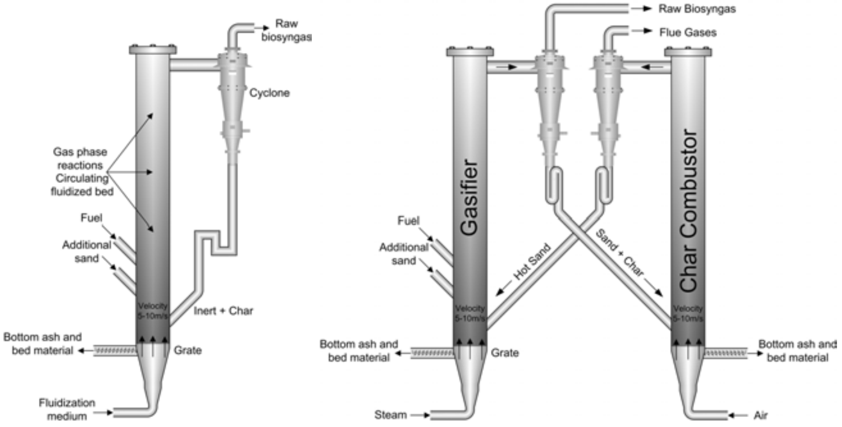

Figure 5: Direct CFB-gasifier (left) and indirect gasifier (right) (reproduced with permission from Olofsson et al., 2005).

The gasification can be atmospheric or pressurised. One big advantage of atmospheric gasification is less complex and costly equipment, but the scale-up range is more limited than with pressurised gasification. Pressurised gasification also has the advantage of smaller-sized process equipment, which can reduce costs for certain types of equipment. Further, as several forms of biofuel synthesis are pressurised, pressurised gasification reduces the need for downstream gas compression. Gas compression is also needed for combustion in the gas turbine of a BIGCC, for which reason pressurised gasification can also be advantageous in BMG applications designed for electricity production.

After the gasification, the gas needs to undergo treatment. The required gas treatment depends on both the downstream use of the syngas and the quality of the raw gas, but in general the gas needs to be cleaned from particulates and substances that can damage process equipment, as well as upgraded to meet quality demands. If the gas is simply to be used as fuel gas, a cyclone separator can be sufficient, while if the gas is to be fired in a gas turbine or upgraded for fuel synthesis, additional particle removal in for example high-temperature filters is necessary.

3.1.3 Syngas upgrading and biofuel synthesis

For BMG processes followed by biofuel synthesis, the demands on gas purity and quality increase significantly. If the gas contains high level of tars and heavy hydrocarbons, these can be cracked catalytically or thermally, to increase the process efficiency and avoid problems with downstream condensation. CH_4 may also need to be reformed, unless SNG is the planned end product. It is also necessary to remove sulphur compounds and other components that may cause catalyst poisoning in for example the biofuel synthesis reactor. This can be done by scrubbing or by physical adsorption.

Before the syngas can be converted into biofuels it also needs to be conditioned in order to achieve the optimal gas composition for the synthesis. In particular, the stoichiometric ratio $(H_2\text{-}CO_2)/(CO+CO_2)$ needs to be adjusted. This ratio depends on the biofuel to be synthesised, but should typically be around 2, while from the gasifier the ratio is significantly lower. Via water gas shift, the stoichiometric ratio is increased by reaction of CO with H_2O. After the shift, CO_2 is removed via absorption or adsorption, before the syngas enters the synthesis reactor.

Several different biofuels can be synthesised from gasified biomass. Below the four different fuels considered in the papers of this thesis are described briefly: methanol, DME, FTD and SNG.

Methanol is produced by hydrogenation of carbon over a catalyst. The synthesis reactions are exothermal, and through reactor cooling steam is produced for use elsewhere in the process. The synthesis can be done in fixed-bed reactors with gas phase reactions, or in slurry reactors with liquid phase reactions. The latter have a higher conversion per reactor passing than conventional fixed-bed reactors, as well as more efficient heat transfer. The methanol is cleaned by distillation, where by-products and water are removed (e.g. Hamelinck and Faaij, 2002; Spath and Dayton, 2003).

The DME synthesis is largely similar to the methanol synthesis, and DME can be formed as a by-product in the methanol process. Typically, the DME process consists of several steps, the first of which is methanol synthesis, followed by dehydration. The synthesis can also be done in one step, using bifunctional catalysts. The DME synthesis is also exothermic and since the catalysts are deactivated at high temperatures, cooling is of large importance. The end product consists of a mix of DME, methanol, water and other by-products, which undergoes treatment via post-reaction of the methanol and distillation (e.g. Spath and Dayton, 2003; Ekbom et al., 2005).

In the Fischer-Tropsch (FT) synthesis a spectra of hydrocarbon chains is produced, from short gaseous to long waxes, including small amounts of branched and unsaturated hydrocarbons. FTD consists of chains with 9-25 carbon atoms. The product mix is controlled by the choice of catalyst and reaction conditions. After the synthesis, produced waxes can be hydrocracked to increase the diesel fraction yield. The reaction is highly exothermic, even more so than the methanol and DME processes. FT reactors can have fixed, fluidised or slurry beds. In the process a certain amount of by-products, such as naphtha, is always produced in addition to the main product (e.g. Boerrigter and Rauch, 2005; Ekbom et al., 2005).

For the three syntheses described above, the syngas composition should typically contain high concentrations of H_2 and CO, and low concentrations of the inert CH_4. If, however, the desired end product is SNG (methane), the gasification process can instead be designed to yield a syngas with high CH_4 concentration. The H_2 and the CO in the syngas are reacted catalytically to form CH_4, in a highly exothermic reaction, which puts demands on the process design (e.g. Boerrigter and Rauch, 2005; Kopyscinski et al., 2010).

As the described biofuel syntheses are all exothermic, a share of the energy content in the biomass feedstock is converted to heat. This heat is recovered for use in the biofuel production chain. Steam is produced at several places in the chain, mainly by gas and compressor cooling, and by cooling of the synthesis reactor. The steam can be used to produce electricity in a steam turbine, and to supply endothermic parts of the process chain, for example biomass drying, water gas shift, distillation and absorbent regeneration.

If a multi-pass reactor is used for the biofuel synthesis, a part of the syngas stream must be diverted in order to maintain gas composition and avoid inert gas accumulation. The off-gas can be combusted and used for additional electricity production, either in the steam turbine system or in a gas turbine.

Electricity is used internally in several parts of the process, a large part of which is oxygen production for the gasifier, in processes employing autothermal oxygen blown gasification. In most of the biofuel production processes studied in this thesis, the internally produced electricity is not enough to cover the process needs, for which reason electricity may also have to be purchased from the grid. In other cases, the process may have a surplus of electricity, which can instead be sold to the grid.

Even with thorough heat integration, the biofuel production chain will still probably have a surplus of heat. In order to increase the overall conversion efficiency, this heat could be used in other industrial processes or in district heating, if located sufficiently close to a district heating network.

3.1.4 BMG-based electricity and heat production

Instead of producing biofuels, the produced syngas can be used for electricity production in steam turbines, gas turbines or gas engines. BIGCC has been of interest for several decades now, due to the possibility of achieving higher electrical efficiency than in conventional combustion-based steam turbine cycles. In the BIGCC process, the cleaned syngas is fired in a gas turbine, after which the gas turbine exhaust is cooled in a heat recovery steam generator (HRSG) to produce steam for the steam turbine. Heat usable for district heating is produced in the steam cycle condenser, with some heat also being produced by syngas and compressor cooling.

For smaller gasifiers, a gas engine could be an alternative. This puts lower demands on the gas quality than when using a gas turbine. Gasified biomass could also be used as fuel gas. One example is as lime kiln fuel in pulp mills.

3.2 Past and present biomass gasification projects

Fossil gasification is today a mature technology, with over 400 gasifiers in operation and an installed capacity of over 56 GW in 2007 (NETL, 2007). The interest in gasification of biomass feedstocks can be described as highly intermittent, and closely linked to market factors such as the oil price. Today only around 20 gasifiers for biomass or waste are in commercial operation, with a total capacity of about 1.4 GW (NETL, 2007; Kirkels and Verbong, 2011). Even though BMG can to some extent build on knowledge gained from coal gasification, the very different fuel properties hinders a smooth transition from fossil to renewable feedstock. Also, while coal has a high energy density and can be found in highly concentrated amounts in specific areas, biomass has a considerably lower energy density and is spatially more scattered, which makes collection and distribution more cumbersome and costly. Despite receiving much attention in recent years in research and demonstration, BMG markets are still very immature and highly dependent on niche applications (Kirkels and Verbong, 2011).

This section describes the current commercialisation status of different BMG concepts, and gives an overview of a number of past and present BMG projects, focusing on European projects. If not otherwise stated, all capacities in the following text concern biomass input. For more information on BMG projects, the PhD thesis by Hellsmark (2010) is recommended. Hellsmark has compiled a comprehensive database of BMG plants, including pilot, demonstration and commercial plants, with a total of over 120 entries.

BMG can today only be seen as a commercial process for less advanced applications. Gasification for use of the product gas as fuel in kilns or boilers, is an example of a commercial BMG application, with a number of gasifiers installed during the 1980's, many of which are still in operation. For example, the Södra Cell Värö pulp mill in Varberg, Sweden, has since 1987 operated a 35 MW CFB gasifier for generation of fuel gas for the lime kiln (Hellsmark, 2010).

Gasification of biomass or waste for co-firing with coal can also be considered as commercial on a large scale, with several plants in commercial operation around Europe. For example, the Kymijärvi power plant in Lahti, Finland, operates a 60 MW CFB gasifier for gasification of low-quality fuels, such as recycled wastes (Knoef, 2005). The gas is co-fired in a coal-fired boiler for steam cycle-based CHP production. The gasifier has been in commercial operation since 1998.

For BMG with gas engine-based electricity production, there are indeed also several plants in commercial operation. In Harboøre, Denmark, a 3.5 MW updraft moving bed gasifier for gas engine CHP has been in operation since 2002 (Knoef, 2005). Also in Denmark, another gas engine CHP plant has been in operation in Skive since 2008. The Skive plant is based on a BFB gasifier with a maximum input of 28 MW (Held, 2010). In Austria, two indirectly heated gasifiers with gas engine CHP are currently in operation. The first plant, the Güssing plant, has been operating an 8 MW indirectly heated gasifier since 2002 (e.g. Hofbauer et al., 2003; Pröll et al., 2007). The second plant, in Oberwart, has been operational since 2009, and is based on a 9 MW gasifier (Held, 2010).

For more advanced BMG applications, commercial status is still some way down the road. BIGCC, which in this thesis is included as an alternative to conventional biomass-based CHP, with higher electrical efficiency, has only been demonstrated with some measure of success in Värnamo, Sweden. In Värnamo, an 18 MW CFB gasifier was in operation from 1993-1999. At the plant, BIGCC CHP technology was demonstrated, using a number of different feedstocks and gathering a total of 8500 hours of operation. Due to low electricity prices at the time, the plant was shut down at the end of the demonstration project[9] (e.g. Sydkraft AB, 2001; Hofbauer and Knoef, 2005). In order to reach commercial status, further technology development is needed, especially concerning gas turbines suitable for the low-value gas resulting from BMG.

For production of liquid fuels from gasified coal, the process is well developed and commercial, with South African Sasol being the main producer of FT fuels from coal. For synthetic fuels from gasified biomass, commercialisation is however still rather far off, even though a number of research and development projects on BMG-based fuel production are currently running. At the Güssing gasifier, the syngas has a low nitrogen and tar content and high heating value, which makes it attractive for biofuel synthesis. At the plant, testing and development of SNG as well as FTD synthesis is being performed (e.g. Hofbauer et al., 2003; Pröll et al., 2007). FTD synthesis has also been in focus for the German company Choren, who has developed Carbo-V, a three-stage gasification process, followed by FTD synthesis. The technology has been demonstrated in a 1 MW pilot plant, and a 45 MW gasification plant has been installed in Freiberg, Germany. The plant was planned as an intermediate scale demonstration plant for FTD production. However, the project has been delayed several times, and in 2009 Shell, one of the major shareholders in Choren, decided to sell its shares. During the summer of 2011, Choren filed for bankruptcy (e.g. Held, 2010; Hellsmark, 2010; Choren, 2011).

At Chalmers University of Technology, Gothenburg, Sweden, a CFB boiler has been retrofitted with a BFB gasifier, to form an indirectly heated BMG process for production of high quality syngas. The gasifier has a flexible capacity of 2-6 MW thermal input, and has been operational since 2007 (Thunman and Seemann, 2009). At the plant, operating conditions of the gasifier and subsequent tar cleaning

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[9] After a few years of downtime, modification of the plant with the purpose of demonstrating downstream biofuel synthesis within the CHRISGAS project, began around 2005. Due to different obstacles the plant operation has now been discontinued.

are planned to be optimised to produce a gas suitable for SNG synthesis. In the related GoBiGas project, also in Gothenburg, Sweden, the goal is to build an industrial scale (20 MW SNG) BMG plant for commercial SNG production (Gunnarsson, 2011). Construction for the first unit is started and planned to be operational in early 2013. Based on the experience from the first unit an extension of the capacity to 80-100 MW SNG is envisaged.

ECN, the Energy Research Centre of the Netherlands, is also conducting research and development of indirectly heated BMG, with downstream conversion to biofuels. Currently, a 10 MW plant demonstrating gasification and gas cleaning, with use of the syngas in a gas engine CHP plant, is scheduled to be put into operation in 2012 in Alkmaar, the Netherlands (van der Meijden et al., 2010). The plant is planned to be an intermediate step towards a 50 MW SNG demonstration plant. In Karlsruhe, Germany, Forschungszentrum Karlsruhe (FZK) has in collaboration with Lurgi GmbH constructed a 5 MW demonstration plant for pyrolysis into intermediate pyrolysis oil, intended to be followed by entrained flow gasification (e.g. Hellsmark, 2010). The project goes under the name Bioliq, and the purpose is technology for downstream upgrading to biofuels.

ETC, Energy Technology Centre in Piteå, Sweden is the centre for research and development of several entrained flow gasification concepts. In the PEBG project, ETC and the Swedish industrial company IVAB are developing a pressurised entrained flow gasifier. The gasifier is rated for 1 MW and is a slagging oxygen-blown gasifier with direct quench. The target application is biofuel production and in the ongoing project methanol production will be demonstrated on small scale. In the VIPP project, ETC and the Swedish industrial company MEVA Innovation have developed a cyclone gasifier for small-scale gas engine-based CHP production. Future plans include production of SNG with a proprietary modification of the process. The pilot gasifier at ETC is rated for 0.5 MW and the industrial CHP demo gasifier which is under commissioning is rated for 4.5 MW. The VIPP gasifier is an atmospheric, air-blown gasifier that works with a wide range of biomass fuels (Gebart, 2011).

3.3 System studies of biomass gasification

Integration of biomass gasification with other parts of the energy system has been analysed in a number of previous studies. This section gives an overview of related system studies of BMG. The studies presented here have been selected to provide a context for this thesis, as well as to describe the research area in which it has been performed. Since this thesis has a Swedish/European perspective, mainly European studies are included.

The possibility of integrating BMG in DH systems has been investigated in several studies, with differing focus for the various analyses. Dornburg and Faaij (2001) compared a number of biomass combustion and gasification technologies for DH heat and electricity production in a general sense, without considering actual DH systems. The analysis was made with respect to costs and primary energy savings, for Dutch conditions. They found that BIGCC performs better than conventional CHP, both regarding relative primary energy savings, and regarding the cost per unit of energy saved, but that at the energy prices at the time, none of the investigated technologies could compete with existing heat and electricity production. They also found that the costs per unit of energy saved were highly sensitive to variations in energy costs and prices, capital costs, plant efficiencies, and heat and power production load factors.

Marbe (2005) analysed integration of BIGCC in CHP applications, both as stand-alone plants and in combination with NGCC[10] in a BIG/NGCC configuration. Marbe concluded that BMG-based electricity production could play an important role in future energy systems, due to the higher electricity production for a given heat load. The results however also showed that within the studied range, a high cost for emitting fossil CO_2 was not enough to make BIGCC or BIG/NGCC profitable, for which reason additional support would be needed, for example in the form of renewable energy certificates. It was also concluded that it is important to account for detailed performance characteristics, such as power-to-heat ratio and minimum acceptable part-load of the BMG plant, as well as the characteristics of the existing heat production, when evaluating opportunities to integrate BMG with, for example, district heating.

Fahlén and Ahlgren (2009) and Börjesson and Ahlgren (2010) performed case studies of forest residue based BMG in Swedish DH systems. Fahlén and Ahlgren studied options for different levels of integration of BMG with an existing NGCC plant in the Gothenburg DH system, both for CHP production and for production of biofuels. In the study, the DH system was modelled with a high level of detail, using the MARTES model[11]. They showed that profitability is highly dependent on the DH system's production mix, the price relation between biomass and fossil fuels, and the cost of policy instruments, such as tradable green certificates for electricity and biofuels. In general, stand-alone production of SNG for use as transport fuel, with DH delivery, was shown to be the most robust solution. Börjesson and Ahlgren studied the cost-effectiveness of BMG technology in DH systems in the south-western part of Sweden. The study encompassed Västra Götaland and Greater Gothenburg, including the 15 largest DH systems in the region, which were modelled with some system-specific level of detail. For the study, the MARKAL model was used[12]. Conventional (fossil as well as biomass based) energy technologies were included as investment alternatives, as were a number of BMG technologies for electricity or biofuel production. The results indicated that BMG can be cost-competitive in DH systems, but that electricity prices and subsidy levels have large influence. While BIGCC CHP would mainly be cost-competitive in Gothenburg, the largest DH system in the region, biofuel plants (DME or SNG) could indeed also reach necessary economies of scale in small- to mid-sized DH

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[10] Natural gas combined cycle.

[11] Simulating DH systems supply model with a detailed time slice division.

[12] Linear programming, perfect foresight, bottom-up, partial equilibrium cost-optimisation model, developed within the International Energy Agency's energy technology system analysis programme.

system, due to a lower relative heat production. In the study it was also concluded that simultaneous targets for increases of renewable electricity and biofuels, could to some extent be counteractive.

Gustavsson and Truong (2011) evaluated the economic potential for BMG-based biofuel and electricity production in a minimum-cost district heating system, with a relatively small heat load. The BMG applications were allowed to compete with conventional heat production technologies for different scenarios. A carbon cost was considered, but no additional support for biofuels or renewable electricity. The biofuel produced in plants integrated in the DH system was assumed to compete with the corresponding fossil fuels, as well as with biofuel from stand-alone plants. It was concluded that BMG-based biofuel production was typically not cost-efficient in the studied DH system. From the results it appears that neither of the studied biofuel plants reached their optimum scale for the studied system. However, no sensitivity analysis of the influence of DH system size was performed. BIGCC was shown to be competitive when a carbon tax was applied.

Schmidt et al. (2010a, 2011, 2010b) used a spatially explicit modelling approach to investigate different options for increased use of forest bioenergy in Austria, including deliveries of heat from BMG plants to DH systems. Different technologies were considered, including pellet production, first-generation biofuels, second-generation biofuels with and without carbon capture and storage (CCS), BIGCC with and without CCS, and conventional biomass-based CHP or heat-only boilers (HOBs). The distribution of biomass supply and transport costs related to feedstock as well as to final energy products, were explicitly considered. Regarding the modelling of DH heat demand, individual DH systems were not considered in detail. Instead, the heating demand was estimated from data on building stocks and heating degree days, with the assumption that only potential DH expansions could provide heat sinks for heat from new bioenergy conversion plants. In Schmidt et al. (2010a) the objective was to evaluate different technologies' cost-efficiency regarding CO_2 emission reduction. It was concluded that at low CO_2 costs, heat production with pellets was the preferred technology, while at high CO_2 costs BIGCC with CCS became more attractive. It was also concluded that spatial heat demand restrictions had a negative impact on the competitiveness of BIGCC. The most comprehensive of the Austria studies (Schmidt et al., 2011) also included agricultural biomass resources, and applied supply curves to endogenously determine the feedstock costs. The focus was on the cost efficiency of various policy instruments in reaching targets for CO_2 emission reduction and fossil fuel substitution. The results showed that if CCS is not available, a CO_2 tax would be cost-effective with regard to both targets, whereas the inclusion of CCS would lead to a trade-off between the two targets.

Leduc et al. (2008, 2009b, 2010a) also used a spatially explicit model, related to the one used by Schmidt et al., to analyse BMG-based methanol production in Austria, southwest Germany, and northern Sweden, respectively. The model was used to determine optimal plant sizes and locations, as well as methanol production costs, using woody biomass from the forest or short-rotational poplar coppice systems as feedstocks. Other studies that have considered spatial factors in the analysis of BMG applications include Alfonso et al. (2009), Yagi and Nakata (2011), and Natarajan et al. (2011). The studies by Alfonso et al. and Yagi and Nakata only considered small-scale BMG applications for heat and power production, in Spain and Japan respectively, while Natarajan et al. considered large-scale BMG in the form of methanol production and BIGCC, for the region of eastern Finland. Natarajan et al. also acknowledged resource competition by including existing biomass users, such as forest industry and CHP or heat plants. Actual DH demand in each municipality in the region was considered, as was the DH share already met by existing CHP/heat plants. The results showed that the spatial distribution of biomass resources and of energy demand density are important factors regarding optimal plant locations, and that methanol plants were typically located closer to the biomass supply, while BIGCC plants were positioned in areas with high heat demand.

Egeskog et al. (2009) assessed the opportunity on a European scale (EU25) to implement BMG-based biofuel production in DH systems, with a focus on the potential offered by the EU25 heat sink capacity. They concluded that the aggregated heat sink of the EU25 is large compared to the amount of surplus heat that would be available if the entire 2020 10% target were to be met by BMG-based biofuels. In fact, only 15% of the total existing heat demand would be necessary as heat sink. However, the national differences were found to be large, as was the impact of where in the heat production dispatch order the BMG plants would be placed. Egeskog et al. also addressed the potential competition between surplus heat from BMG plants and existing and new base load production, such as other industrial excess heat, heat from waste incineration, and CHP heat.

Joelsson (2011) assessed various applications using Swedish biomass resources (mainly forest biomass) regarding the potential to cost efficiently reduce CO_2 emissions and oil use. A process-based, aggregated approach was used, with extensive discussion concerning the impact of the assumed reference system. Biofuel production (BMG-based as well as lignocellulosic ethanol) was included, as were various stationary applications, such as small-scale heating and CHP. It was concluded that the highest potential to reduce CO_2 emissions and limit resource use would generally be obtained if using the limited biomass resources in stationary applications. However, in the longer term forest-based biofuels could contribute to reduced CO_2 emissions, especially if coal-based transport fuels are broadly introduced. A strategy for reduced emissions and fossil fuel use was suggested, including BIGCC CHP in district heating systems, and transport fuel production based on BLG in chemical pulp mills rather than on BMG in stand-alone facilities. It was also concluded that gasification of biomass feedstocks is a key technology to achieve large reductions, regardless of whether the reduction of CO_2 emissions or of oil use is prioritised.

Most system studies of integration of gasification with pulp and paper production focus on black liquor gasification, but studies have also been made of integration of solid biomass gasification. Consonni et al. (2009) assessed different biorefinery concepts, considering gasification of both solid biomass and black liquor, for integrated pulp and paper production in the United States. They concluded that once commercialised, those concepts may play a vital role in the pulp and paper industry, as they offer a potential for both attractive investment returns and significant energy and environmental benefits. At VTT a comprehensive techno-economic study of various BMG and BLG concepts for Finnish conditions was made (McKeough and Kurkela, 2007; Saviharju and McKeough, 2007). It was concluded that the high availability of excess heat from gasification-based biofuel production makes integration suitable with an energy-demanding industrial facility, such as paper or integrated pulp and paper production, which have a steam deficit that in general is covered by a power boiler. Integration with market pulp production could also be possible, if a part of the black liquor stream is diverted from incineration in the recovery boiler, and instead upgraded by, for example, gasification or lignin separation. Joelsson (2011) also studied biofuel production integrated with pulp and paper production, comparing BLG- and BMG-based concepts. BLG-based biofuel production was found to reach a higher system efficiency than BMG-based production, due to the larger integration potential in relation to the produced amount of pulp or paper.

The studies mentioned above apply very different systems perspectives, ranging from techno-economic engineering studies with a high level of detail of the BMG applications, to broad systems analyses with a high degree of simplification for the included technical applications. This thesis combines technical knowledge of biomass gasification with systems analysis, as well as a local perspective with a supranational perspective, and complements and advances previous studies.

4

Studied systems

This chapter describes the systems studied in the papers of this thesis. The analysed integration of biomass gasification in each of the studied systems is also described. At the end of the chapter, a summary of the biomass gasification applications considered is given, with comments on the input data used.

Three different systems have been studied in this thesis. Two are local Swedish cases (one district heating system and one pulp and paper mill), while the third system study is performed on the European level. All the papers included biofuel production, based on autothermal fluid bed gasification, and four of the papers (I-IV) also included BMG-based electricity production. The biofuel considered differed between the papers, depending on in which context the papers were written, and which system was studied. A black- or grey-box approach was used for the integration calculations, based on publicly available engineering studies.

Figure 6 shows a schematic overview of BMG-based biofuel production, as studied in this thesis. As shown in the figure, the biofuel production process has a surplus of heat that can be utilised in other parts of the energy system, and which forms the basis for the integration analyses performed.

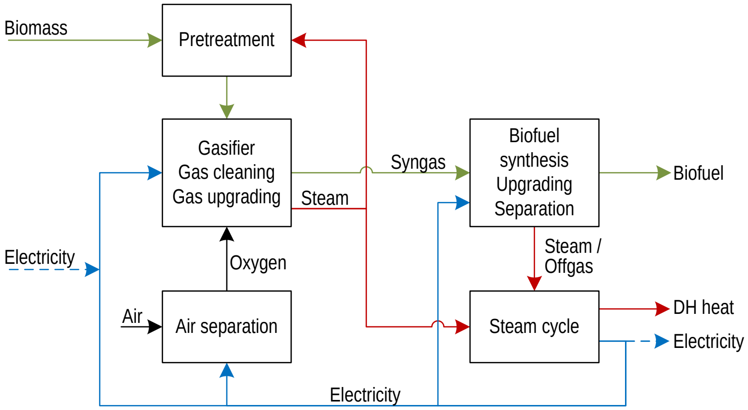

Figure 6: Schematic overview of BMG-based biofuel production. Note that some of the biofuels give a surplus of electricity while others have a deficit. DH heat can also originate at other places in the process.

4.1 District heating system – the case of Linköping

In Papers II-III the district heating system of Linköping was used as a case study. The DH system is managed by Tekniska Verken Linköping AB, and is connected to the adjacent municipality of Mjölby via a DH transmission pipeline, which makes it one of Sweden's largest DH systems. Besides residential heat, Tekniska Verken also delivers industrial process steam and heat, and district cooling.

Figure 7 shows the annual heat load duration curve and the existing heat production. Waste incineration constitutes the base heat load production, with the waste incineration plant consisting of two facilities. The first is a modern CHP plant with a steam turbine and flue gas heat recovery (FGHR). The second is a hybrid CHP plant, which was constructed to produce electricity through the operation of an oil-fired gas turbine, the flue gases of which were used to superheat the steam from the waste incineration for expansion in a steam turbine. When the gas turbine was initially installed, oil prices were low, which made operation profitable. However, since then oil prices have increased, and in recent years the gas turbine was hardly ever operated. At the time of making the study (late 2007-early 2009), Tekniska Verken was looking at options for replacing the gas turbine. One of those was a BMG-fired external super-heater, the "waste boost process". However, since the publication of Papers II-III, the CHP plant has instead been retrofitted with a new low-pressure steam turbine, making both gas turbine and waste boost obsolete (Difs, 2010).

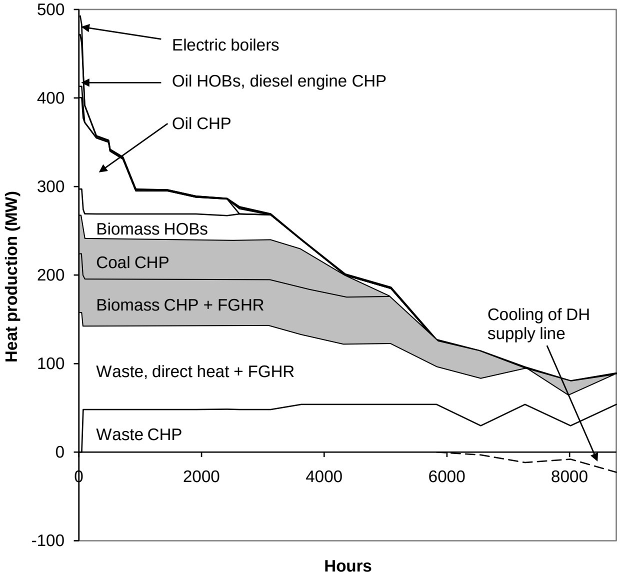

Figure 7: Annual heat load duration curve for the Linköping DH system (2007). Shaded areas indicate plants planned to be taken out of operation.

In addition to the waste incineration plants, there is another CHP plant with three boilers, fired by waste wood, coal and oil, respectively, and a number of oil or biomass fired heat-only boilers (HOBs), as well as electric boilers. On the whole, the DH system of Linköping contains a variety of facilities, which gives the DH system a large degree of fuel and operational flexibility. Moreover, there is the possibility to cool the DH network supply line, in order to increase electricity production during the summer when the DH demand is low.

Two CHP boilers are planned to be taken out of operation since they will reach their maximum technical lifetime, which results in a need for investment in new heat production capacity in the DH system. As options for new heat production, conventional combustion-based steam cycle CHP and four BMG-based alternatives were considered. Since Linköping already has a well developed biogas distribution system, SNG as BMG biofuel product was a logical choice. BMG-based electricity production in the form of BIGCC was included in both papers, and in Paper II biomass integrated gasification gas engine (BIGGE) CHP, and the "waste boost process" mentioned above were also considered. Those two applications are not further discussed in Part 1 of this thesis. Details can be found in Paper II.

The integration calculations were made using a black-box approach, with publicly available studies of BMG applications with DH delivery being used to provide the input data. Figure 8 shows the modelled structure of the Linköping DH system. The new investments (dashed boxes) were allowed to compete with each other for the heat load made available by the plants taken out of operation (shaded).

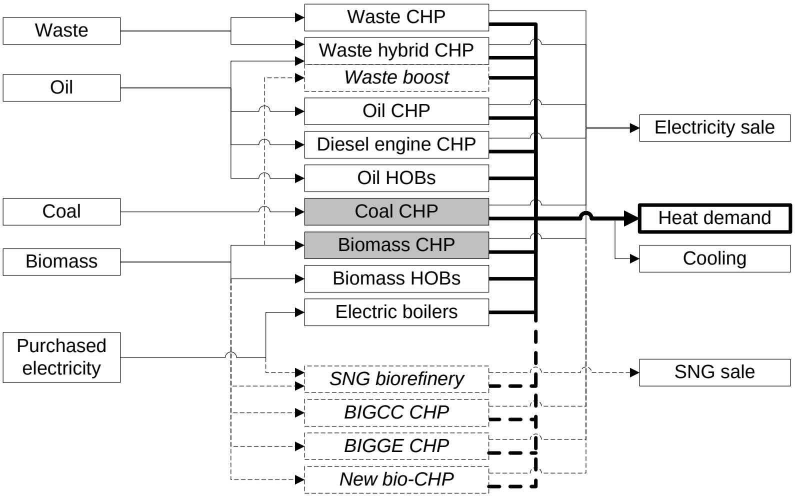

Figure 8: Overview of the Linköping DH system, as modelled in Papers II-III. Dashed lines and italicised text indicate investment options. Shaded boxes indicate existing plants planned to be taken out of operation.

4.2 Pulp and paper mill – the case of Billerud Karlsborg

In Papers IV-V the integrated pulp and paper mill of Billerud Karlsborg was used as a case. The mill, located outside Kalix in northern Sweden, produces bleached kraft pulp and sack and kraft paper. The mill incorporates batch digesters, but for the study performed for this thesis was approximated as applying a continuous digesting process. High pressure steam is produced in the recovery boiler and in a power boiler, fired mainly with falling bark and purchased wood fuel. Internally produced tar oil is used as fuel for the lime kiln. Electricity is produced in a backpressure turbine with intermediate extraction of steam at two levels. The maximum power output of the turbine is 44 MW, but with the current production and demand of steam it usually delivers around 30 MW. Excess low pressure steam can be vented. The in-house electricity production covers approximately 70% of the mill's electricity demand, and the rest is purchased from the grid.

Biomass gasification could be integrated in the mill by using the heat surplus from the BMG process to replace steam from the bark boiler, thus creating a biorefinery. Two different BMG-based biorefinery concepts were considered – BMG followed by DME synthesis (BIGDME)[13] and BIGCC. The integration calculations made were more thorough than for the Linköping DH system case described above.

The BMG plants were dimensioned to deliver the same amount of steam to the mill as the bark boiler does in the existing mill. The BMG plant steam systems were integrated with the mill's steam system with one common steam turbine, with steam data being adapted to the mill's steam system. Low grade heat was assumed to be used in the mill's secondary heat system for make-up water and condensate preheating, and for production of low pressure steam via very low pressure steam compression. Falling bark originally used in the bark boiler was assumed possible to use in the BMG processes, with purchased forest residues as additional fuel.

Figure 9 shows an overview of the gasification concepts integrated with the mill. For further details of the integration assumptions, see Paper IV.

4.3 EU second-generation biofuel market

In Papers VI-VII the system studied was the European Union. The objective was to develop and use a spatially explicit model suitable for studies of opportunities and locations for second-generation biofuel production in the EU. The entire EU27, with the exception of the two small island nations of Malta and Cyprus, was included. The model is described in more detail in Section 5.4.2.

In general, the biofuel interest on the continent lies mainly with liquid biofuels that are easy to integrate into existing infrastructure. For this reason, three liquid biofuels were included in the study: methanol, FTD and lignocellulosic ethanol (in Paper VI only methanol and ethanol)[14]. The only integration possibility included

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[13] DME was chosen as biofuel product due to the considerable current interest for DME in northern Sweden.

[14] Lignocellulosic ethanol is not further described here. For details, see Papers VI and VII.

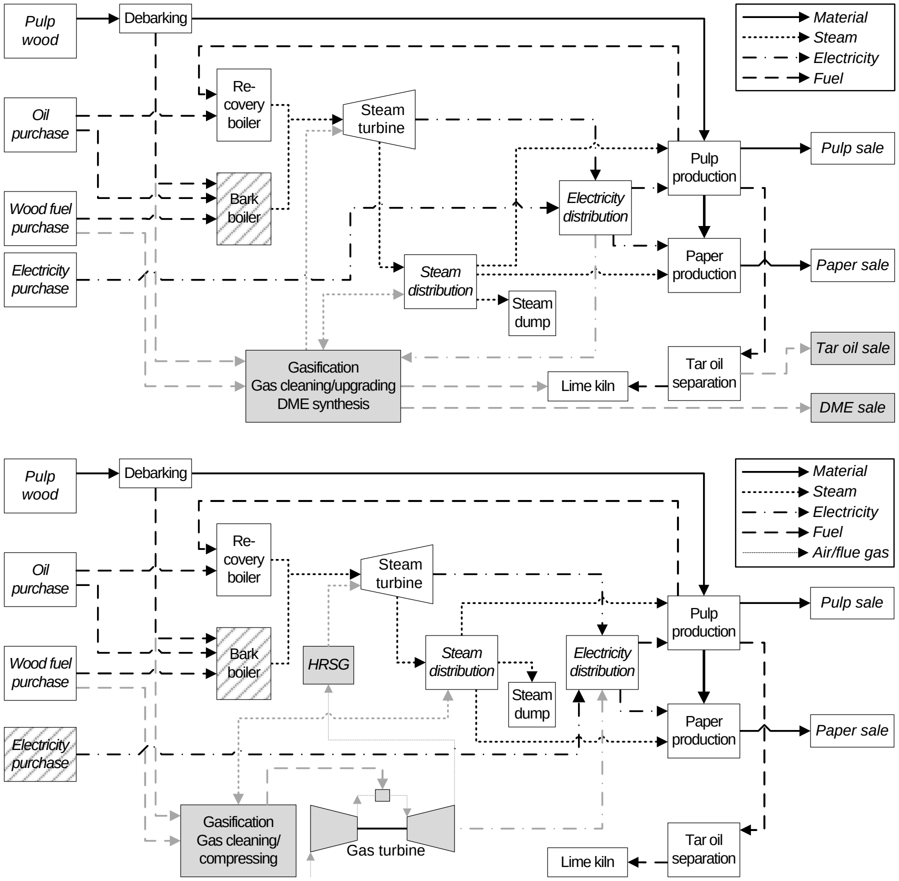

Figure 9: Overview of DME production (top) and BIGCC (bottom) integrated with the pulp and paper mill, as modelled in Papers IV-V. Grey boxes and flows indicate new processes compared to the original mill. Hatched boxes indicate processes included only in the original mill. Excess low grade heat has not been included in the figure.

at the stage of model development described here was with DH systems. A black-box approach was used, with excess heat assumed possible to sell to DH systems if a heat demand was available, or else wasted[15]. Co-produced electricity was assumed possible to sell directly to the grid, with no limitation on demand.

Contrary to Papers II and III, where one DH system was modelled in detail, Papers VI and VII did not consider individual DH systems at all. Instead the total national DH demand, including an expansion potential, was downscaled assuming

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[15] At a later stage of model development, the plant design could be adapted if no heat demand exists. Due to computational limitations, this option has not yet been included.

that the district heating demand is proportional to the population of each grid point. The DH systems were described on a nationally aggregated level, with the heat delivered from the biofuel production plants assumed to displace heat corresponding to a heat mix specific to each country. It was assumed that all existing fossil DH heat could be replaced by heat from the biofuel production plants, as well as a share of the current non-DH fossil heat. For details on the DH expansion potential in the EU, see Werner (2006), Egeskog et al. (2009) and Wetterlund (2010). A simplified heat load duration curve was applied, with different load profiles to accommodate for variance in annual load distribution at different latitudes.

4.4 Biomass gasification in this thesis – summary

The biofuel production processes included in this thesis, as well as the BIGCC process, are all scalable to large sizes, that is, several 100 MW biomass capacity. Table 2 gives an overview of the process efficiencies and scale ranges used in the papers of this thesis, for plants integrated with district heating. For details of conversion efficiencies for BMG integrated with pulp and paper production, see Papers IV and V.

Three of the papers (I, IV-V) applied a static approach with fixed plant sizes, while the other four papers (II-III, VI-VII) involved partly dynamic optimisation where the plant sizes were selected by the optimisation model. As can be seen from the table, different input data or different scale ranges have in some cases been used for the same technology.

Table 2: Net efficiencies and scales for the large-scale BMG technologies considered in this thesis. Negative electrical efficiencies indicate a deficit of electricity. Efficiencies and scales concern LHV (lower heating value) of biomass input at full plant load. For data on lignocellulosic ethanol, see Papers I and VI-VII, and for DME via BLG, Paper I.

		Efficiency			
	Papers	Biofuel	Electricity	DH heat	Scale (MW)
Methanol[a]	I	0.54	-0.057	0.057	229
	VI-VII	0.55	0	0.11	110-450
DME	IV	0.65	-0.053	0.15	200
FTD	VII	0.52	0.073	0.067	110-450
SNG	II-III	0.69	-0.041	0.23	150-300 (II) 150-400 (III)
BIGCC[a]	I	–	0.43	0.43	140
	II	–	0.43	0.47	20-300
	III	–	0.43	0.47	20-400
	IV	–	0.41	0.41	54

[a] For data on methanol and BIGCC with CCS, see Paper I.

For methanol, the input data used in the first paper (Boding et al., 2003) did not contain investment data of sufficient detail, for which reason data from Hamelinck and Faaij (2002) was used for the other papers considering methanol (VI-VII).

Since the results from Paper II indicated a need for larger maximum scale for the BMG applications, in order for them to be able to meet the entire available heat demand, the scale ranges of both the SNG plant and the BIGCC were increased for Paper III.

For BIGCC, the input data for the first study was chosen because it contained the possibility to include CCS (Uddin, 2004; Uddin and Barreto, 2007). However, the investment data was not sufficiently detailed to fit the methodology in Papers II-III, for which reason data from Marbe et al. (2004) and Bärring et al. (2000) was used instead. For Paper IV more detailed steam data was needed, which could be found in a study by Harvey (2000).

5

Methodology

This chapter presents the methodologies and energy market scenarios used in the papers of this thesis.

Five of the papers of this thesis included evaluation of the impact on global CO_2 emissions. Of those, two papers (I and IV) employed a more comprehensive system expansion approach, while in the others (II, VI and VII) a simplified analysis was carried out. All papers except Paper I included techno-economic evaluation of BMG applications in different systems. In five papers (II-III, V and VI-VII) this was done using optimisation models, while Paper IV applied a spreadsheet model. Table 3 gives an overview of the methodologies and approaches used.

Table 3: Overview of methods and approaches in the appended papers.

Method/approach	Paper						
	I	II	III	IV	V	VI	VII
Comprehensive CO_2 analysis	●			●			
Simplified CO_2 analysis		●				●	●
Techno-economic evaluation		●	●	●	●	●	●
Optimisation		●	●		●	●	●

5.1 Evaluation of effects on CO_2 emissions

When evaluating the performance of a biomass conversion facility in terms of effects on global fossil CO_2 emissions, different approaches can be used, and, for each of the steps in the conversion chain, different choices can be made. The result is that different studies may come to very dissimilar conclusions regarding, for example, the climate impact of a certain biofuel. In this section a short discussion about a number of key issues is given, together with a description of the approaches used in the papers of this thesis.

In general terms, a life cycle perspective should be adopted and the full biomass conversion chain, from plant growth to end use, included in the analysis. When evaluating climate impact and energy efficiency of biofuels and other transportation options, a well-to-wheel (WTW) perspective is usually applied. A WTW study is a type of life cycle assessment (LCA) that is normally limited to the fuel cycle, from feedstock to tank, and vehicle operation, typically focusing only on air emissions and energy efficiency (MacLean and Lave, 2003; Edwards et al., 2007). A WTW study can be divided into two parts – the well-to-tank (WTT) part, which includes the process steps from feedstock to tank, and the tank-to-wheel (TTW) part, which basically includes the vehicle operation.

5.1.1 General methodology considerations

The first step in the CO_2 emission evaluation is to identify and define the system boundaries. The system boundaries can be viewed as cut-off points, beyond which the studied system neither has any significant effect, nor is significantly affected by the surroundings. In general, any activities expected to affect or be affected by the studied system should be included. This can however be hard to achieve, especially since the environmental consequences of a product or process are more than only the direct effects from production and use. Thus, when making life cycle-related analyses of emerging technologies, such as second-generation biofuels, the analysis should not be limited to direct effects, but also include indirect effects, as discussed for example by Ekvall and Weidema (2004) and Sandén and Karlström (2007).

Next, a baseline or reference system must be defined. The reference system constitutes an estimate of what would have occurred in the bioenergy project's absence. The reference system should include alternative pathways for included materials and energy carriers, such as transport fuel, electricity and heat. The choice of reference system depends on the aim and time frame of the study. The reference system should in general constitute a close alternative to the studied system and use the same technology level. One crucial concern is the choice between average and marginal technologies for the reference system. The use of a marginal approach is generally recommended for change-oriented studies of possible future systems, particularly for comparison between different systems (e.g. Tillman, 2000; Ekvall and Weidema, 2004; Sandén and Karlström, 2007).

One heavily debated issue in LCA methodology is co-product allocation, which has been shown to be a key issue influencing GHG emissions and energy efficiency results in WTW and LCA studies of biofuels (e.g. Larson, 2006; Gnansounou et al., 2009; Börjesson, 2009). Allocation can be done based on physical properties, such as mass or energy content, or based on economic value. As discussed by Börjesson (2009), one advantage of energy allocation is that the relations between different by-products remain constant over time, while economic allocation is based on data that fluctuates over time. The results of economic allocation can however be more rational in systems with large amounts of low-value co-products, such as straw from grain-based ethanol or low grade heat. Allocation on energy basis for biofuel production co-products is for example dictated in the EU renewable energy directive (European Parliament, 2009a).

Through system expansion or substitution, allocation can be avoided. This is done by expanding the system's boundaries to include the additional functions of all products from the system. System expansion is not without limitations of its own. Examples are the issue of selecting the correct substitute, the need for accurate life cycle data on the alternative product or products, and that system expansion itself might cause new allocation problems, as discussed by for example Gnansounou et al. (2009) and Finnveden et al. (2009). System expansion is recommended by the ISO standard for life cycle assessment (ISO, 2006), where it is also acknowledged that allocation avoidance is not always practically possible.

Another issue concerns the choice of functional unit[16]. If biofuels are compared to each other and/or to fossil fuels, and if the full WTW chain is considered, the service provided (for example the distance travelled) can be chosen as the functional unit (e.g. Edwards et al., 2007). If biofuel production is compared to other bioenergy alternatives, another functional unit must however be chosen. Several studies, for example by Schlamadinger et al. (1997) and Gustavsson et al. (2007), emphasise the importance of considering the limiting resource. For bioenergy systems this will typically be the available amount of biomass or the available land for biomass production.

Issues related to allocation and choice of functional unit become increasingly complicated for processes involving the co-production of several products, which is the case for example with many biorefinery concepts. If a biomass conversion process is integrated with other industries or district heating systems, further difficulties arise. For example, if system expansion is used for a system with a relatively low biofuel output and a large output of a particular by-product, such as low-grade heat, a high CO_2 emissions reduction potential may be erroneously attributed to the properties of the biofuel when it is really an effect of the large heat output. To counter this problem, either the reference entity could be expanded so that all compared systems produce the same output (Schlamadinger et al., 1997), or the functional unit could be expanded to include all products (Gustavsson and Karlsson, 2006). Expanding the functional unit may, however, lead to the inclusion of unlikely components in the studied system, such as biomass-fired condensing plants. Further, when comparing very different systems or systems of a very complex nature there is a risk for losing transparency.

5.1.2 Methodological choices in this thesis

To varying extent, the papers of this thesis are all based on system expansion. A WTT approach has been used for the CO_2 emission evaluations of biofuel production facilities, with the exception of one paper (I), in which the entire WTW chain was considered. The papers have considered systems of different size – one industry, one municipal energy system, and one international energy system. However, even though the inner system boundaries encompass differently sized systems, a similar approach has been used in all papers.

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[16] Quantitative measure of the function of the studied system, that provides a reference to which inputs and outputs can be related.

When expanding the system, a number of surrounding systems need to be regarded. Figure 10 shows a schematic overview of the CO_2 evaluation methodology used in this thesis, for a biomass conversion process, including surrounding systems that need to be considered[17]. As shown in the figure, it is assumed that net flows of energy and material entering or leaving the biomass conversion facility affect the surrounding systems.

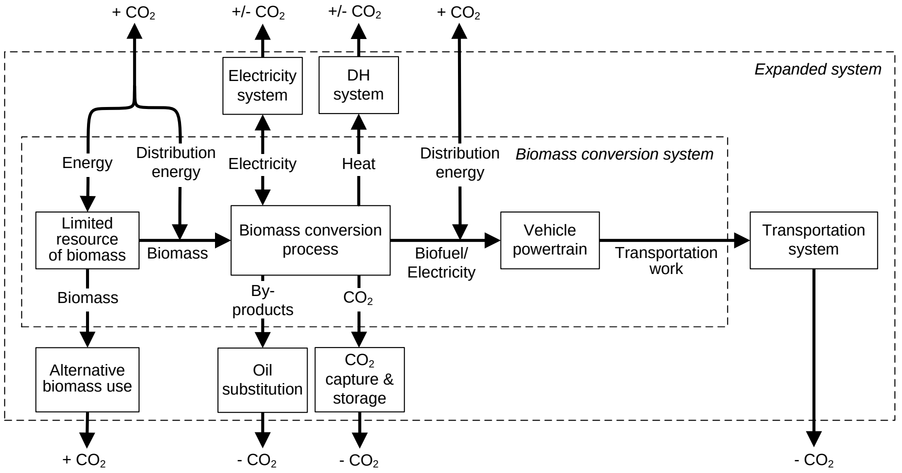

Figure 10: Schematic representation of a biomass conversion process, and its interactions with the surrounding system. The effect on CO_2 emissions of each flow is indicated with +/-, where + means an increase and - a decrease in CO_2 emissions.

In all papers, a European perspective has been applied, including for the studies of local Swedish systems. Here, the considered reference systems are described briefly. Details are given in the respective papers.

For electricity it has been assumed that a net surplus or deficit of electricity affects the marginal European electricity production. Base load build margin, rather than operating margin, has been considered, due to the relatively long time frame for the performed studies (Kartha et al., 2004). The base load build margin is defined as the type of electricity production, the building of which is affected by the implementation of, for example, a new biomass conversion facility. The papers of this thesis considered various fossil marginal electricity technologies. One paper (I) also considered CO_2-lean electricity, such as wind power. For district heating, the reference production is of a much more local character, which makes determination of a margin technology difficult, impossible, or even nonsensical. Two papers (I and II) used conventional steam cycle biomass CHP as alternative technology, assuming that it would be the alternative investment for the studied system. In one paper (IV) an attempt was made to use a more marginal approach, implementing fossil heat. Two papers (VI and VII) considered national heat mixes.

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[17] Not all flows in Figure 10 are explicitly discussed here. See Paper I for more details.

The reference transportation technology has in all papers been assumed to be fossil based. Only one paper (I) explicitly considered vehicle technology, while the other papers assumed that biofuels substitute fossil fuels on a 1:1 energy ratio. Today, oil-based fuels dominate the transport sector, for which reason gasoline and/or diesel have been considered as reference transport fuels in all papers. However, since the global crude oil supply is dwindling, the marginal transport fuels of the future could be coal based. Paper I investigated this possibility, in addition to the oil-based reference fuels.

Bioenergy is in a general sense often viewed as carbon neutral, under the implicit assumption that the CO_2 emissions associated with the combustion of for example a tree will be fully balanced by the sequestration over the tree's growth period. However, as discussed for example by Schlamadinger et al. (1997), bioenergy production systems are dynamic systems, with a number of CO_2 effects not directly related to the combustion process, but rather to land-use changes. The CO_2 effects from land-use change can effectively offset the emission decrease from substituting fossil fuels, if land with a high carbon stock (for example forest land or peat land) is cultivated (Reijnders and Huijbregts, 2003; Börjesson, 2009). Land-use change effects are typically higher for first-generation biofuels than second, and soil carbon dynamics have not been considered in any of the included papers. Further, as mentioned in Section 2.1, biomass is a limited resource and it is thus not possible to solve the whole climate problem by substituting biomass for fossil fuels. In the future, the available forest biomass is likely to be subject to fierce competition from the traditional forest industry, as well as from new and existing bioenergy users. When evaluating the CO_2 effects from biomass use, and if the same feedstock is in demand for other purposes, an alternative biomass use should be included, as the increased use of a resource with constrained production volume results in less of that resource being available for other parts of the system.

Two of the papers in this thesis (I and IV) consequently employed a more comprehensive approach and expanded the biomass system to include alternative biomass use. In those papers it was assumed that additional demand for biomass in the studied conversion facility will have indirect effects in the form of increased fossil fuel use elsewhere in the expanded system, with a corresponding increase of CO_2 emissions. It was assumed that the high-volume user with the highest willingness to pay will constitute the marginal biomass user. Small-scale biomass users, such as industrial CHP or boiler fuel substitution, often have high willingness to pay. However, their total demand is limited, which is why they can not be regarded as high-volume users. Co-combustion with coal in coal power plants was instead regarded as the marginal biomass use.

Papers II, VI and VII applied a simplified CO_2 analysis, with the more conventional assumption that the use of biomass does not cause increased CO_2 emissions. The main reason for not applying the more comprehensive approach, was that in-depth CO_2 evaluation was not the main focus of those papers. The simplified CO_2 analysis applied can be viewed as a preliminary screening of the CO_2 reduction potential, in a system where biomass use is not limited. In Section 6.4 the impact of those assumptions is evaluated further, through additional analysis.

The only GHG species considered is CO_2. When the feedstock is forest residues, the exclusion of other GHG species does not significantly affect the total GHG emissions from the biomass conversion chain (see e.g. Edwards et al. (2007)). However, for grid electricity production based on fossil fuels the contribution from other GHG such as methane could be significant.

5.2 Techno-economic evaluations

Techno-economic evaluation has been included in all papers except Paper I. Common for all papers is that investment data from the literature has been used. This can be problematic, especially when comparing BMG concepts from different sources and from different years. Within each paper, a base year has been chosen, to which all investment data has been adjusted, using the Chemical Engineering Plant Cost Index (CEPCI, 2010) and currency indexes.

Most plant concepts have been assumed scalable (see Section 4.4). Investment costs have been scaled using the general relationship:

$$\frac{C}{C_{base}} = \left[\frac{S}{S_{base}}\right]^{R} \tag{1}$$

where C and S represent the investment cost and plant capacity, respectively, for the new plant. C_{base} represent the known investment cost for a certain plant capacity S_{base}, and R is the scale-up factor. An overall scale-up factor of 0.7, the average value for chemical process plants (Remer and Chai, 1990), has been used in all papers.

Investment costs have been discounted using the annuity method. Economic lifetime and interest rate differ slightly between the papers, but in general a capital recovery factor of around 0.1 has been used, representing a rather strategic view of the investments[18]. Within each paper, the same capital recovery factor has been used for all possible investments. Individual factors would require a deeper analysis of the expected lifetime of each investment, as well as of risks associated with the investment. This kind of analysis has been outside the scope of the studies in this thesis. Several of the papers instead contained sensitivity analysis of the capital recovery factor.

5.3 Energy market scenarios

Four of the papers (II-V) used energy market scenarios with interdependent parameters for the economic analysis, while the other two papers (VI-VII) used actual energy prices for the EU member states, and biomass feedstock costs from a forest growth model.

The scenarios used in Papers II-V reflect different future energy market conditions, and were constructed using a methodology and a tool, the Energy Price

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[18] Corresponding to, for example, an interest rate of 6% and an economic lifetime of 15 years.

and Carbon Balance Scenarios (ENPAC) tool, developed by Axelsson and Harvey (2010). Inputs to the ENPAC tool include fossil fuel prices and assumed values for policy instruments, in particular the cost for emitting fossil CO_2. Based on these inputs, the marginal technology for electricity generation is determined by assuming that the technology with the lowest cost of electricity production (including capital cost) constitutes the base load build margin. The resulting build margin determines the electricity price for industrial high-volume users, as well as the CO_2 emissions associated with marginal electricity use. In scenarios with low CO_2 charge, the lowest cost technology is typically coal condensing power, while in scenarios with high CO_2 charge, low-emitting technology, such as coal power with CCS or NGCC, will have the lowest production cost.

The biomass market price is calculated based on the willingness to pay of a specified marginal biomass user category, which in turn also determines the CO_2 emission consequences of marginal use of biomass, under the assumption that biomass is a limited resource. In this thesis, coal power plants were in general assumed to constitute the price-setting user group. Consequently, the biomass price was decided by both the coal price and the CO_2 charge. Thus, in scenarios with a high cost of emitting fossil CO_2 the biomass price will be high, which seems reasonable, since high CO_2 costs will likely lead to higher demand and fiercer competition for bioenergy.

Finally, the willingness to pay for excess heat on the district heating market is determined based on the price-setting technology in a certain heat market. The calculation flow is shown in Figure 11. By using this procedure, consistent future energy market scenarios can be constructed, containing energy prices and costs as well as CO_2 emissions related to marginal use of energy.

The ENPAC scenarios were originally constructed to be used for analysis of energy intensive industry. Some adjustments were made for the papers of this thesis, in order to adapt the scenarios to the studied systems. Different versions of the scenarios were used for the different papers. All sets of scenarios were based on two different fossil fuel price levels and two different levels of CO_2 cost, resulting in four scenarios. For details, see the respective paper.

In addition to the CO_2 charge, three other policy instruments were included in the papers of this thesis – green electricity certificates (Papers II-IV)[19], energy taxation (Papers II-III), and support for biofuel production in the form of, for example, green certificates or tax exemption (Papers II-VII)[20].

The biofuel price was set so the end user has the same cost per unit of fuel energy for the biofuel as for the corresponding fossil fuel. It was assumed that biofuels are subject to energy tax, but not to any CO_2 charge. The biofuel selling price is thus affected by the levels of fossil fuel price as well as by the assumed level of CO_2 charge placed on fossil fuels.

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[19] In Paper V, model runs were made including electricity certificates, but since they turned out to have very little impact, the results from those runs were removed due to space limitations for the paper.

[20] The form of biofuel policy support has not been explicitly analysed, and could for example be in the form of tradable certificates, a feed-in-tariff, or tax exemption.

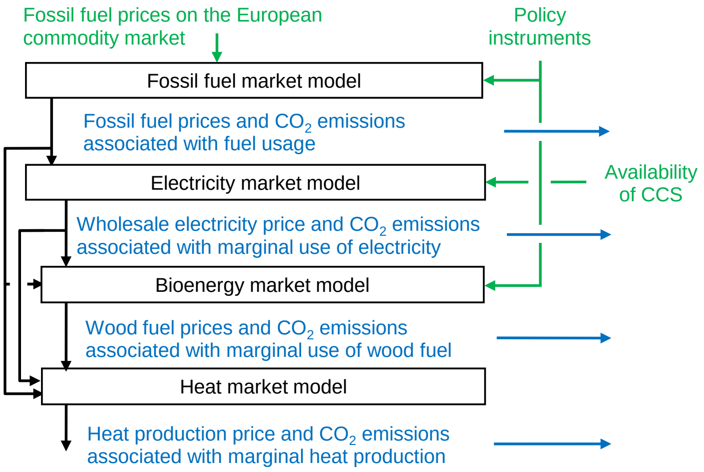

Figure 11: Overview of the ENPAC tool calculation flow. Green arrows represent required input, boxes calculation units for the different energy markets, black arrows information flows within the tool, and blue arrows output, i.e. energy market parameters (reproduced with permission from Axelsson and Harvey (2010)).

Papers II-III employed scenarios with considerably lower costs associated with energy and policy instruments than in the scenarios of Papers IV-V, as did Papers VI-VII. For this thesis, additional analyses have been made of both the Linköping system (Papers II-III) and of the EU system (Papers VI-VII), applying the Paper IV/V scenarios. Table 4 presents those scenarios.

5.4 Energy systems optimisation

With increasingly complex energy systems, and an increasing desire to reach more efficient systems, the need for satisfactory computer-based decision support is large. When mathematical relations can be identified in the studied system, mathematical programming can be applied. Mixed Integer Linear Programming (MILP) is a well established method that can combine technical and economic data of a studied energy system, and use it to determine optimal strategies that minimise the energy cost for the system, as discussed for example by Arivalagan et al. (1995) and Karlsson (2002, 2011).

A MILP problem contains the objective function that is to be minimised or maximised, variables (real and integer) and constraints, which represent separate restrictions that limit the possible solution space. The integer variables can be used to consider a choice, for example if a new plant is built or not, or if a facility is operating or not. Non-linear functions, such as Equation 1 in Section 5.2 above, can be linearised in discrete steps using integers, and thus be included in the MILP problem. MILP problems are solved using different mathematical algorithms. On a general form, a minimising MILP problem can be described as

Table 4: Paper IV/V energy market scenarios, complemented with energy carriers as needed for the additional analysis for Papers II-III and VI-VII.

Scenario		1	2	3	4
Fossil fuel price level		Low	Low	High	High
CO_2 charge		Low	High	Low	High
Prices and policy instruments					
Wood chips	EUR/MWh	36	66	40	70
Wood byproduct	EUR/MWh	31	57	34	60
Waste wood	EUR/MWh	19	34	21	36
Waste	EUR/MWh	-16	-8	-16	-8
Electricity	EUR/MWh	68	90	74	98
Heavy fuel oil[a]	EUR/MWh	34	34	57	57
Light fuel oil[a]	EUR/MWh	57	57	87	87
Tar oil (selling price)	EUR/MWh	34	34	57	57
Biofuel (selling price)	EUR/MWh	57	77	88	109
District heating	EUR/MWh	19	49	27	56
CO_2 charge	EUR/t_{CO2}	35	109	35	109
Green electricity certificates	EUR/MWh	26	26	26	26
Biofuel policy support[b]	EUR/MWh	46/0	67/0	20/0	41/0
CO_2 effect (kt_{CO2}/GWh)					
Electricity		0.679	0.129	0.679	0.129
Biomass with/without marginal effects		0.227/0	0.244/0	0.227/0	0.244/0
Oil and tar oil[c]		0.295	0.295	0.295	0.295
District heating		0.242	0.468	0.242	0.468
Biofuel[d]		0.281	0.281	0.281	0.281

[a] Excluding CO_2 charge.

[b] The scenarios are applied with as well as without biofuel policy support.

[c] Tar oil is assumed to replace heavy fuel oil.

[d] Replacing a mix of diesel and gasoline as transport fuel.

$$\begin{aligned} \min_{x,y} \quad & \left[\sum_{n=1}^{N} c_n x_n + \sum_{k=1}^{K} e_k y_k \right] \\ s.t. \quad & \sum_{n=1}^{N} a_{n,m} x_n + \sum_{k=1}^{K} d_{k,m} y_k = b_m, \quad m = 1, \dots, M \\ & y_k \in Z, \quad k = 1, \dots, K \end{aligned} \tag{2}$$

where N is the number of continuous variables, K is the number of integer variables, and M is the number of constraints. x are the continuous variables and y are the integer variables. a, b, c, d, and e are parameters, and Z is the set of all integers.

MILP models of energy systems have been used in Papers II-III, V and VI-VII to optimise energy systems of different types and sizes.

5.4.1 reMIND

For two of the systems studied in this thesis, reMIND MILP models were used (the Linköping DH system in Papers II-III and the Billerud pulp and paper mill in Paper V). reMIND is a java-based decision support software utilised to implement the MIND method (Method for analysis of INDustrial energy systems), which is a method developed to optimise dynamic energy systems, using MILP. The MIND method and reMIND have been developed at Linköping University (see e.g. Nilsson (1993) and Karlsson (2011)). The development is ongoing, with new functions being added in accordance with the users' needs.

When constructing a model using reMIND, the structure of the modelled system is represented as a network of branches and nodes. The branches represent flows of, for example, energy or material. The nodes denote process components, and can represent, for example, an entire industry, a process line or a single machine. Each node can be assigned any number of functions to describe the functionality of the depicted component. Time dynamics of the modelled system are captured by a flexible time division, to account, for example, for hourly, daily or seasonal variations. Figure 12 shows the basic user interface of the reMIND software.

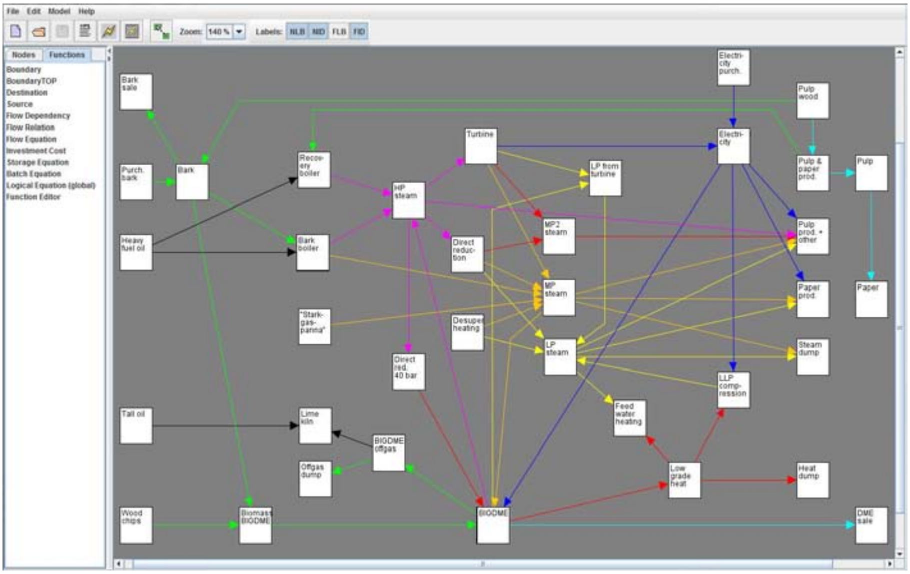

Figure 12: User interface of reMIND, showing a simplified version of the pulp and paper mill model used in Papers IV-V.

When running the reMIND model, the mathematical MILP problem and its matrix of equations (see Equation 2) is generated in a standardised format. The MILP problem is solved using an appropriate optimisation routine. For reMIND, the commercial solver CPLEX is usually used, using simplex to solve the linear programming problem, and branch and bound to solve the integer programming problems (Thollander et al., 2009). Usually the objective is to minimise the system cost while satisfying a given demand, by choosing the optimal alternative regarding, typically, operation and new investments. The system cost comprises all costs that are included in the model, such as capital costs, energy and material costs, and operation and maintenance (O&M) costs. Revenues, for example from sold products, are included as negative costs.

The MIND method was originally developed for analysis of various types of industrial energy systems, but due to its large degree of flexibility, it can be used to model other types of energy systems as well. Energy systems where the MIND method has previously been used include forest industry (Bengtsson et al., 2002; Karlsson and Wolf, 2008), iron and steel industry (Larsson et al., 2004; Thollander et al., 2009), and interactions between industries and DH networks (Jönsson et al., 2008; Svensson and Moshfegh, 2011).

5.4.2 BeWhere

For the EU system (Papers VI-VII), the BeWhere model was used. While reMIND is a tool that can be used to construct a MILP model of any energy system, BeWhere is a specific, geographically explicit MILP model designed for analysis of optimal locations for bioenergy conversion facilities, in particular for biofuel production. The model has been developed in the commercial software GAMS and is solved using CPLEX. Model development has been done continuously over several years at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and at Luleå University of Technology. BeWhere has previously been used for regional studies, for example of Norrbotten (Leduc et al., 2010a) and eastern Finland (Natarajan et al., 2011), and national studies, for example of Austria (Schmidt et al., 2010a, 2011), Sweden (Leduc et al., 2010b) and India (Leduc et al., 2009a).

For the studies in this thesis, BeWhere was further developed to encompass biofuel production in the entire EU. The model was used to determine the location and size of biofuel production plants, given the locations of feedstocks and energy demand. In order to limit calculation times, the EU was divided into eight regions delimited by natural borders, such as water or mountains. Each region was in turn divided into grid cells with a half-degree spatial resolution (approximately 50 x 50 km), where each grid cell serves as both supply point for forest biomass, demand point for energy (transport fuels and DH heat), and potential site for biofuel production. A network map of roads, rails and shipping routes was used to compute transportation routes and distances between supply areas and production plants, as well as between plants and demand areas. Demand for transport fuels as well as for DH heat was included. Trade points, situated at major harbour locations and strategically located border points, were defined for interchange of biomass and biofuel between regions. Figure 13 shows the regions and the trade points.

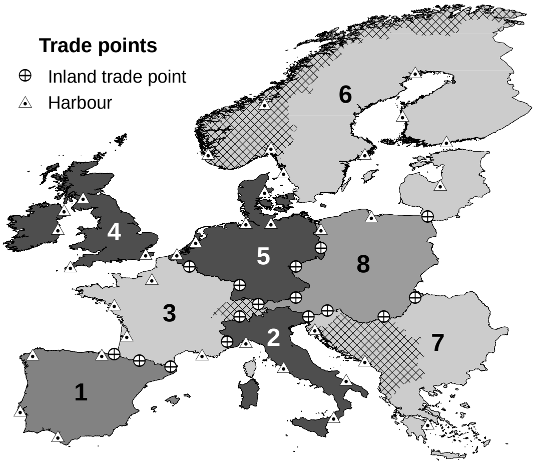

Figure 13: Regions and trade points in the BeWhere EU model used in Papers VI-VII. Hatched areas are non-EU countries that are not included in the model.

The objective of the model is to minimise the total cost of the complete biofuel supply chain, including biomass harvest, biomass transportation, conversion to biofuels, transportation and delivery of biofuel, and sale of excess heat and co-produced electricity. Fossil CO_2 emissions are also considered, by applying a cost for emitting CO_2 on the supply chain emissions, including a negative cost for offset emissions from replaced fossil energy carriers. The model chooses the least costly pathways from one set of feedstock supply points to a specific production plant and further to a set of biofuel demand points. The resulting output from the model consists of the location of a set of plants, flows of feedstock and biofuel between different parts of the EU, and the cost and CO_2 emissions of the supply chain. For a more detailed description of the BeWhere model, see Leduc (2009) and Wetterlund (2010).

6

Results and analysis

This chapter presents a selection of results from the appended papers, in relation to the research questions around which this thesis is focused. This chapter also includes new results from analysis conducted after the publication of the papers.

For an overview of the relation between research questions and papers, see Table 1 in the introductory chapter. For more discussion regarding the individual results, see the respective paper.

6.1 Investment opportunities

1. Can investment in large-scale biomass gasification technology be an economically attractive option for integration with …

(a) … district heating?

(b) … pulp and paper production?

(a) Biomass gasification in district heating systems

Investment in BMG in DH systems has been analysed in Papers II-IV and VI.

Papers II-III used the Linköping DH system as a case study. Of those, Paper III aimed at investigating the levels of policy support needed to make large-scale BMG applications competitive, which is covered in Section 6.2.

Paper II shows that the two included large-scale BMG applications – BIGCC CHP and SNG production – could both be economically competitive to the reference technology conventional biomass CHP, under the energy market conditions considered. With BMG in the DH system, the co-production of high value products would increase significantly, resulting in low-cost heat that could even be competitive with heat from the waste incineration plants. Sensitivity analysis of various assumptions showed that removal of existing plants, increase of the heat load, and possibility to cool the DH supply line were not prerequisites for BMG. However, both large-scale technologies were shown to be highly dependent on the type and size of economic policy support.

Paper IV used integration of BMG with DH systems as a comparison to integration with a pulp and paper mill. Contrary to Paper II, where the heat demand was driving the need for investments in new heat production capacity and co-produced biofuels or electricity were viewed as the by-products, Paper IV used an approach where the main objective was to build the BMG plants, and co-produced heat was the by-product. For each of the two BMG technologies considered – BIGCC CHP and DME production – the investment opportunity was calculated and compared to investment cost estimates found in the literature. The results show low or no investment opportunity for the BIGCC plant, with a high sensitivity to heat price assumptions as well as to policy support. The DME plant show considerably higher investment opportunity, with equally high sensitivity to the policy support, but with lower sensitivity to the heat price, due to a lower relative heat delivery.

Both Paper II and Paper IV applied energy market scenarios with interdependent parameters, as described in Section 5.3. Since the scenarios in Paper IV employed significantly higher energy prices, it is difficult to compare the results between the papers. For this reason, the analysis from Paper II has been repeated applying the Paper IV/V scenarios[21], with as well as without biofuel policy support. The reMIND model of the Linköping DH system was also updated to accommodate for issues identified during the original work[22]. As in Paper II, investment in biomass CHP was considered as a reference for each studied scenario. In the rest of this chapter the original scenarios from Paper II are denoted *Old scenarios*, whereas the Paper IV/V scenarios are denoted *New scenarios*.

Table 5 summarises the results regarding new investments, production of electricity and SNG and resulting system costs for the Linköping DH system, for the old as well as for the new scenarios. In general, the pattern between the old and new results is very similar. Only two of the old scenarios (labelled 3 and 4 here, 5 and 6 in Paper II) contained biofuel policy support, for which reason only those two scenarios resulted in investment in an SNG plant. All of the new scenarios employ rather high biofuel support, which makes SNG production profitable in all four scenarios. Without biofuel support, SNG production is not profitable in any scenario. BIGCC is only profitable in scenarios 1 and 3, contrary to the old scenarios, where it was also profitable in scenario 2.

To understand the results, it is necessary to understand the scenarios and the interrelation between different energy carrier prices. Figure 14 shows the key price ratios in each of the scenarios. In general, the biomass prices are significantly higher in the new scenarios, which is due both to higher fossil fuel prices, and to considerably higher assumed CO_2 cost levels. With higher CO_2 charge, biomass is assumed to become increasingly more interesting for coal substitution, which drives up the prices. The electricity prices and transport fuel prices are also affected, but to a lesser extent. As Figure 14 shows, the electricity-to-biomass price ratio is higher in the old scenarios, which explains the inclusion of BIGCC in one more scenario.

Table 5 also includes the resulting system costs for each scenario, in relation to the corresponding reference scenario. Scenarios with similar solutions with the old and new prices (scenarios 3 and 4 with biofuel policy support, and scenario 1 without support), have comparable system cost results.

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[21] Paper II also included two scenarios using current energy prices, which have not been further analysed. Scenario 1 here corresponds to scenario 3 in Paper II, scenario 2 to scenario 4 etc.

[22] The maximum BMG plant size was increased to 400 MW to be able to cover the entire available heat load, and the model was limited to allow only one new investment in each scenario.

Table 5: Summary of results for the Linköping DH system. Original results from Paper II (old scenarios) and results using new scenarios (with and without biofuel policy support). All results are in relation to the respective reference scenario.

Scenario	Scenarios	CHP	BIGCC	SNG	Prod. El.	(TWh/y) SNG^{a}	System cost (MEUR/y)
1	Old	●	●		+0.45	–	–10
	New			●	–0.36	+2.3	–48
	New-no supp.		●		+0.44	–	–7.5
2	Old	●	●		+0.37	–	–2.4
	New			●	–0.33	+2.3	–63
	New-no supp.	●			–	–	–
3	Old		●	●	+0.16	+1.7	–37
	New			●	–0.36	+2.3	–43
	New-no supp.		●		+0.44	–	–6.1
4	Old	●		●	–0.18	+1.7	–33
	New			●	–0.33	+2.3	–47
	New-no supp.	●			–	–	–

[a] The higher SNG production in the new scenarios is due to increased maximum size.

To be able to compare the results from Paper II to the results from Paper IV, the BMG investment opportunity has been calculated for the Linköping DH system, from the resulting annual system costs. The resulting investment opportunities are shown in Figure 15 in relation to ranges of investment cost estimates found in the literature, for the Linköping DH system as well as for the unspecified DH system in Paper IV. For both DH systems, the biofuel plants are well within or above the reported investment cost range when a forceful biofuel policy is applied. When the policy support is halved, two scenarios (3 and 4) still show some promise, which is due to the higher biofuel-to-biomass price ratio in those scenarios, while there is no or very low investment opportunity when the policy support is removed.

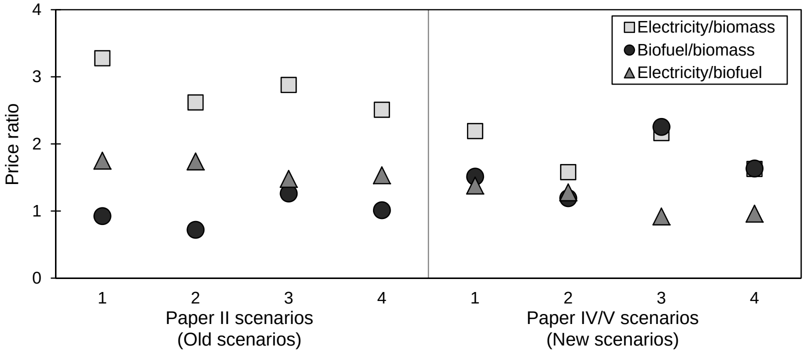

Figure 14: Ratios between energy carrier prices in the scenarios applied in the different papers. All prices are without added policy support.

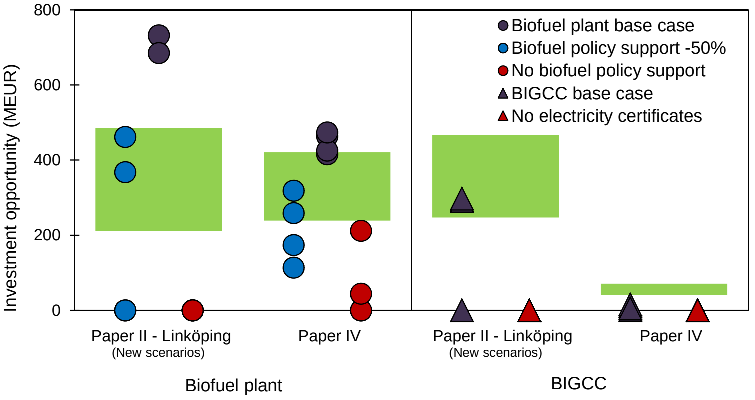

Figure 15: Investment opportunity for biofuel plants and BIGCC in district heating systems (over four scenarios). The green areas represent the ranges of investment cost estimates found in the literature for correspondingly sized plants (SNG: (Börjesson and Ahlgren, 2010; Gustavsson and Truong, 2011; McKeough and Kurkela, 2007), DME: (Elam, 2002; Boding et al., 2003; Hamelinck and Faaij, 2006), BIGCC: (Harvey, 2000; Dornburg and Faaij, 2001; Marbe et al., 2004; Bridgwater and Bolhàr-Nordenkampf, 2005)).

That certain scenarios show zero investment opportunity for biofuel plants in the Linköping system is due to the MILP optimisation model used for the Linköping system, with integer variables defining whether a plant is built or not.

For BIGCC the results are slightly more optimistic for the Linköping system than for the Paper IV system. In two scenarios (1 and 3, when no biofuel policy was included), the resulting investment opportunity actually reaches the reported investment cost range for the Linköping system, while it falls well short of the reported range in the corresponding scenarios, for the Paper IV system. The reason is that in the Linköping system the BIGCC competes with another high-cost investment in the form of new biomass CHP, while in Paper IV the assumed alternative production has lower heat production costs. It is clear for both DH systems that without policy support, no investment opportunity can be found.

Integration of BMG-based biofuel production with DH systems was also investigated in *Paper VI*, where it was assumed that European biofuel production plants can sell heat to DH systems in order to increase their profitability. Similar to the results in Papers II and IV, the results show no investment opportunity in DH systems without policy support. The possibility to deliver heat to DH systems, as well as the assumed heat price, affects both the biofuel supply cost, and the type and number of biofuel production plants. A high heat price and the possibility to integrate biofuel production with DH, lead to a higher share of ethanol plants, since the ethanol plants have higher co-production of heat than BMG-based biofuel plants.

(b) Biomass gasification in a pulp and paper mill

Investment in BMG integrated with a pulp and paper mill was analysed in Papers IV and V. The results from Paper V, which focused on policy support analysis, are discussed in Section 6.2.

Paper IV analysed whether BMG (BIGCC or DME production) integrated with a pulp and paper mill could be economically competitive with investment in a new bark boiler. The Billerud Karlsborg mill was used as a case. Figure 16 shows the resulting investment opportunity, in relation to estimates found in the literature. In particular the BIGCC performs significantly better when integrated with the mill than with the comparison DH system discussed above (compare with Figure 15). This can be explained mainly by integration effects and, to some extent, also by longer annual operating time when integrated with the mill. The increased electricity production in relation to the increased biomass input is significantly higher when integrated with the mill than with the DH system[23]. This advantage can also be observed for the DME plant, although to a lesser extent.

For both the DME plant and the BIGCC, the investment opportunity drops when the policy support is decreased. However, contrary to the DH cases, the investment opportunity actually also reaches the reported investment cost range with no policy support. For BIGCC the investment opportunity reaches the reported range in all scenarios, and for the biofuel plant in the scenario with highest biofuel-to-biomass price ratio (scenario 3). The assumption that the bark boiler would need replacement is not a prerequisite under the analysed energy market conditions.

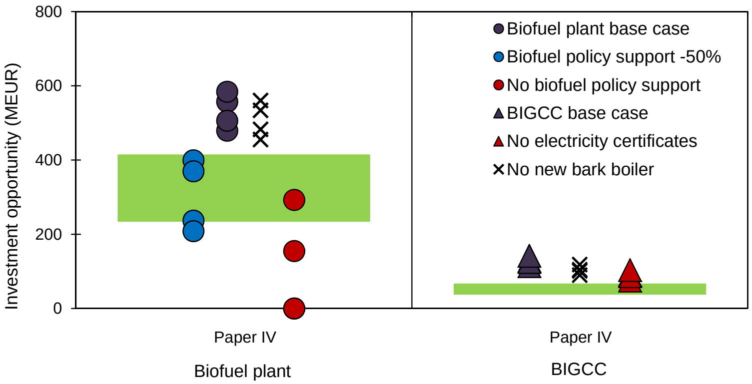

Figure 16: Investment opportunity for biofuel production and BIGCC integrated with the pulp and paper mill (over four scenarios). The green areas represent the ranges of investment cost estimates found in the literature for correspondingly sized plants (DME: (Elam, 2002; Boding et al., 2003; Hamelinck and Faaij, 2006), BIGCC: (Harvey, 2000; Dornburg and Faaij, 2001; Marbe et al., 2004; Bridgwater and Bolhàr-Nordenkampf, 2005)).

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[23] See paper IV, Table 2.

6.2 Need for economic policy support

2. What levels of economic policy support are needed to make investments in biomass gasification technology economically attractive?

The question about necessary policy support for BMG to become economically attractive, has been analysed in four of the papers (III and V-VII). Common for the papers is that optimisation models have been used, applying different energy market scenarios. The cases studied, the approaches and the scenarios used have however been relatively disparate. In order to be able to make a broader comparison of the results, additional analysis has therefore been made here.

Paper III used the Linköping DH system as a case study, and *Paper V* the Karlsborg pulp and paper mill. Both papers included analysis of the level of biofuel support needed to make investment in biofuel production competitive, while Paper III also included analysis of the level of electricity certificates needed to make investment in BIGCC competitive to investment in a conventional steam cycle-based CHP plant. Due to considerably higher prices and costs of energy in Paper V, as well as a revised methodology for calculating the biofuel gate selling price[24], the results are not directly comparable between the papers. For this reason, the analysis from Paper III has been repeated applying the new scenarios (Paper IV/V scenarios) on the updated Linköping reMIND model (see Section 6.1).

Papers VI-VII studied biofuel production on an EU level and included analysis of the necessary policy support to reach a 3% second-generation biofuel share in the EU, considering two policy instruments: a CO_2 emission cost and targeted biofuel support. In this section the biofuel support results from *Paper VII* are discussed. The analysis of the support needed to reach 3% has also been repeated using the new scenarios, applying uniform energy costs and prices for the entire EU.

Table 6 summarises the original support results from the papers, as well as the updated results. For the Linköping DH system the results show a remarkable range, both over the scenarios within one group of results (original or new), and between the groups. A first reflection is that the way the biofuel selling price is calculated, is of large significance. When the analysis in Paper III was performed, the actual output from the model consisted of the total revenue for sold biofuel, from which the gate selling price was subtracted to obtain the sought-after required support level. Since the assumed relation between the crude oil price and the transport fuel pump price obviously has a large impact (a factor 2), it would have been interesting to have also included a discussion on this subject in the original analysis.

When looking at the results using the new scenarios, the results for the scenarios based on low oil prices are comparable to the corresponding results using the old scenarios, while for the scenarios based on high oil prices the needed support

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[24] In Paper III, the biofuel gate selling price $P_{biofuel}$ (EUR/MWh) was calculated as $P_{biofuel} = 1.3P_{oil} + C_{CO2} - C_{distr}$, where P_{oil} is the crude oil price, C_{CO2} the CO_2 tax applied to fossil transport fuels, and C_{distr} the biofuel distribution cost. The factor 1.3 represents the price difference between crude oil and refined fuel (Edwards et al., 2007). In Paper V, the selling price was instead calculated as $P_{biofuel} = 1.2P_{oil} + 18.1 + C_{CO2} - C_{distr}$ (Axelsson and Harvey, 2010).

Table 6: Necessary support levels for BMG-based biofuel production or BIGCC to be profitable. Includes original results from Papers III, V and VII, as well as updated results for Paper III and VII. Result ranges over four energy market scenarios, except for original Paper VII results. BF = biofuel, DH = district heating, P&P = pulp and paper.

	Necessary support levels (EUR/MWh)			
	BF support DH system	BF support P&P mill	BF support EU	El. cert. DH system
Paper	III	V	VII	III
Original results	24-42	11-61	34	0
Adjusted fuel price[a]	11-22	–	–	–
New results[b]	0-31	–	0-30	13-68

[a] Paper III results adjusted using updated selling price calculation method[24].

[b] Using the Paper IV/V scenarios.

is significantly lower with the new scenarios. The pulp and paper mill shows a similar biofuel support pattern – low need for support in the scenarios with high oil prices, and higher in the scenarios with low oil prices. Contrary, for BIGCC to be competitive no support for green electricity was needed when using the old scenarios, while with the new scenarios applied the need for support is considerable, exceeding 60 EUR/MWh in two of the scenarios (2 and 4).

For the EU study, the original results show that with current European energy prices, a biofuel support of 34 EUR/MWh would be needed to reach 3% biofuels. Without any policy support, no biofuel would be produced. At higher fossil fuel prices, the necessary policy support decreases rapidly, to about half the level required at current prices with a fossil fuel price 25% higher than today. With even higher prices, a significant biofuel share could also be reached with no policy support. When applying the new scenarios to the EU system, the required support is comparable to the support needed in the Linköping DH system. This is interesting, as the favoured location for biofuel production in the EU study is indeed DH systems, as is further discussed in Section 6.3.

To understand the results, it is again necessary to understand the scenarios and the interrelation between prices and costs of different energy carriers. As discussed in Section 6.1, the biomass costs are in general significantly higher in the new scenarios. For the electricity certificates the results are easily understood from Figure 14 – with a significantly higher electricity price in relation to the biomass cost in the old scenarios, there is no need for further support. Contrary, the biofuel-biomass price ratio is higher in the new scenarios, in particular in scenarios 3 and 4, which gives lower required support. In fact, in scenario 3 (high oil price, low CO_2 cost) there is no need for policy support in either the DH system or in the EU. This can seem surprising, considering that in the updated results for Paper II, scenario 3 does not present any incentives to invest in biofuel production without policy support (see Table 5). However, the new scenarios include electricity certificates, which just tips the investment opportunity in favour of biomass CHP.

Concerning the required biofuel support in the Linköping DH system versus in the pulp and paper mill, the necessary support is significantly higher in the case of the pulp and paper mill. This can be explained by differences in the fundamental properties of the systems studied. In the DH system, investment in new heat production is a prerequisite, which means that the gasification plants competes with another relatively costly investment (conventional biomass-fired CHP), whereas in the mill, no alternative investment has been assumed.

None of the papers have explicitly addressed the topic of policy support system design, only the level of support needed to make the BMG-based production competitive. The way the study in Paper III was conducted, the support for green electricity was added to the electricity price, in a similar way as in the existing certificate system. With the assumed electricity prices, the needed support would range from just over 10 to almost 70 EUR/MWh. This can be compared to current Swedish certificate levels of around 20 EUR/MWh, and to the certificate levels of other European countries, from below 20 to over 130 EUR/MWh (see Figure 2). However, the results can also be looked at as a feed-in tariff equivalent to the resulting certificate level plus the used electricity price, in which case a feed-in tariff of over 160 EUR/MWh would be needed in the scenario with the highest need for support. This is significantly higher than the current tariffs for biomass-based electricity in any European country, as also shown in Figure 2.

Similarly, the biofuel policy support could just as well be in the form of a feed-in tariff, as a tradable green certificate or a tax reduction. The needed support, at assumed biofuel selling prices, would range from 0 to around 60 EUR/MWh, depending on the studied system. 60 EUR/MWh is above the current average support for ethanol, but still significantly lower than the tax reduction in many European countries, among them Sweden, where the support from tax exemption amounts to almost 90 EUR/MWh (see Figure 3).

6.3 Promising locations

3. What could be suitable locations for future large-scale biomass gasification plants?

The question of localisation of BMG plants has mainly been addressed in Paper VI. Here, the results from Papers II and IV are also discussed in the broader perspective given by research question 3.

The results discussed in Section 6.1 for research question 1, show that investment in large-scale BMG could be economically attractive under certain conditions, in the studied DH system as well as in the studied pulp and paper mill. Generalisation from single cases is difficult, considering that the two cases studied here both represent highly site-specific types of systems. However, it is possible to make a rough estimate of the number of similar systems, which could be of interest for further studies.

For the biofuel plant in *Paper II* (updated results), the DH heat output for the preferred plant size is just under 100 MW, while for the BIGCC plant the heat output almost reaches 200 MW, which gives the BIGCC plant shorter annual operating time than the biofuel plant. With the original maximum plant sizes the heat output still reaches 70 and 140 MW, respectively. Due to the high capital costs it is reasonable to assume that BMG plants would need to operate as base load or just above base load in the heat production dispensing order. In Sweden there are presently around twenty DH networks with an estimated base load over 70 MW[25]. Of those, a majority are already dominated by heat production based on biomass, waste or waste heat. In order to be able to determine whether any networks could be a real option for investment in BMG, more detailed studies would need to be made, taking into account for example type and age structure of the existing production, as well as competition with existing or new CHP production.

Concerning pulp and paper mills, there are currently fourteen chemical integrated pulp and paper mills in Sweden, similar to the mill studied in *Papers IV-V*, and five mechanical integrated pulp and paper mills, that can be assumed to have a steam deficit that could be further investigated as potential heat sinks for excess heat from BMG.

Figure 17 shows the Swedish DH systems and pulp and paper mills that have been identified as being of interest for future studies of integration of BMG.

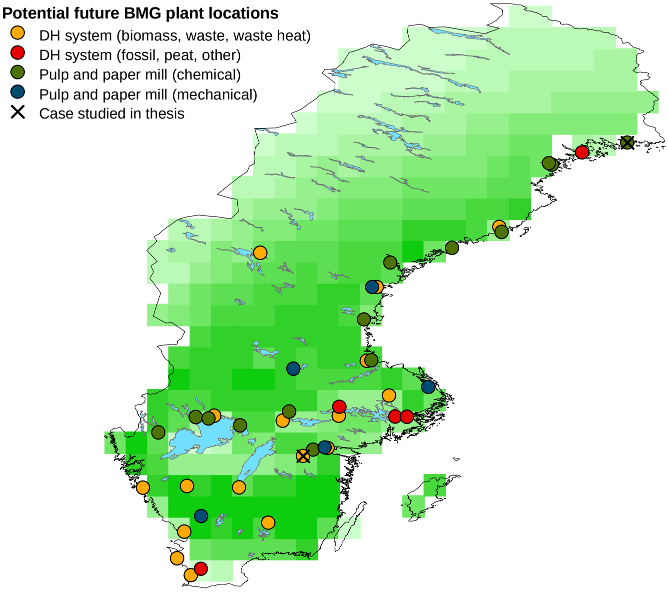

Figure 17: DH systems with an estimated base heat load of more than 70 MW and pulp and paper mills with potential heat deficit (Swedish District Heating Association, 2009; Swedish Forest Industries Federation, 2011). The background shading represents the annual increment of forest biomass (based on Paper VI-VII data). The Linköping DH system and the Billerud Karlsborg mill are also marked.

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[25] The base load sizes have been estimated from annual production statistics (Swedish District Heating Association, 2009), applying a standard load shape to the total heat delivery.

Figure 17 also shows the annual growth of forest biomass in Sweden. As can be seen, most of the identified interesting systems are indeed located close to areas of high annual forest growth. However, much of this biomass is likely already in use, for industrial purposes or for existing CHP or heat production plants. For this reason, future studies of BMG feasibility should include competing biomass use.

The issue of geographic plant localisation, taking into account distances to supply sources as well as to the locations of demand for different energy carriers, has been explicitly addressed in *Paper VI*. The paper aims to investigate how the optimal locations of second-generation biofuel production plants on a European scale are affected by various parameters, such as economic policies, energy costs and prices, heat delivery possibilities, and capital costs. Three different base scenarios have been used: one without policy support, one applying a CO_2 cost, and one applying biofuel support. For each base scenario, a number of parameter variation scenarios have been analysed. In the 39 total scenarios tested, the optimal number of biofuel production plant ranges from 0 to 87, with the second-generation biofuel share in the EU spanning from 0 to over 4%. Without policy support, no plants are included in the optimal solution. Figure 18 shows the geographic distribution of the optimal plant locations, grouped by number of occurrences over all studied scenarios.

In general, the plants should be located close to where the availability of reasonably priced biomass is high. This is especially pronounced for region 6 (Sweden, Finland and the Baltic states) and for the northern parts of region 1 (Spain).

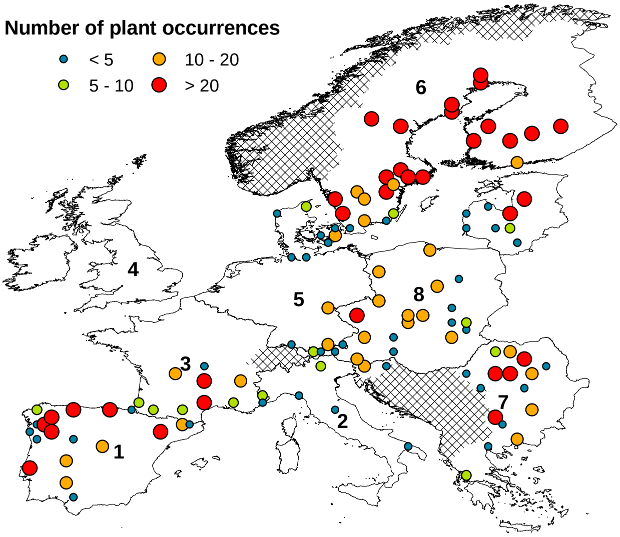

Figure 18: Number of biofuel plant location occurrences in Paper VI, over 39 studied parameter variation scenarios. Hatched areas are non-EU countries that were not included in the analysis.

Since the transport fuel demand is low in large parts of northern EU in particular, not all produced biofuel can be utilised in the production region. Instead biofuel is exported to other regions. Regions with high population densities and low availability of biomass feedstock have little or no production of their own. This includes region 2 (Italy), region 4 (UK and Ireland), and region 5 (Germany, Belgium, the Netherlands and Denmark). Those regions meet most or all biofuel demand with imported fuels, while region 6 acts as a net exporter.

As the studied biofuel production technologies have a reasonably high co-production of heat, the resulting plant locations are typically located in populated areas. However, in reality not all of those locations are likely to be suitable for large-scale biofuel production, due for example to high land and biomass prices, biomass logistics issues, or underdeveloped or non-existing district heating systems.

6.4 Effects on CO_2 emissions

4. How would implementation of large-scale biomass gasification technology affect global fossil CO_2 emissions?

Five of the papers in this thesis include evaluation of the impact on global CO_2 emissions. Of those, Papers I and IV have employed a more comprehensive system expansion approach, while in Papers II, VI and VII a simplified analysis has been carried out. In the simplified approach, biomass is not considered as limited, for which reason no marginal biomass use is regarded. Here, additional analysis of the results from Papers II and VI has been performed, applying the comprehensive approach where biomass is considered as limited.

The aim of *Paper I* was to show the impact of system expansion, including the systems surrounding a biomass conversion system, when evaluating well-to-wheel (WTW) CO_2 emissions for biomass-based transportation options. Four illustrative transportation cases were considered: DME via BLG, methanol via BMG, lignocellulosic ethanol, and electricity from BIGCC in a battery-powered electric vehicle. All cases were considered with as well as without CCS. System expansion was used for all flows. The results were compared to the results from a conventional WTW study by Edwards et al. (2007), here referred to as “the EU WTW study”. To highlight the influence of the surrounding systems on the CO_2 results, the reference system was varied systematically, thus covering a large number of possible future energy systems. For more details, see Paper I.

The results shows that when the reference electricity production and transportation technologies are varied, the potential for CO_2 emissions fluctuates, with BMG-based methanol and ethanol in particular showing little or no emission reduction potential, unless biomass use is viewed as CO_2-neutral. The influence of the marginal electricity production differs between the studied cases, due to energy balance differences. BLG-based DME, with a substantial electricity deficit, shows the largest variation, and benefits from a low-emitting reference electricity production (coal with CCS or CO_2-lean electricity). Ethanol, methanol and

BIGCC shows lower dependence on the reference electricity technology, due to low net surplus or deficit of grid electricity. Alteration of the reference transportation system introduces a larger degree of variation in the resulting CO_2 emissions, for all studied cases. The reason is that the biofuel production (electricity production in the BIGCC case) is higher than the deficit or surplus of electricity. If coal-based synthetic fuels (without CCS) were to be widely introduced in the transport sector, the CO_2 effect of biofuels would be considerable, even when regarding biomass as limited.

When comparing the results in Paper I to the results from the EU WTW study, the EU WTW study in general shows a significantly higher potential for CO_2 reductions. Only when biomass use is regarded as CO_2-neutral are the results from Paper I in line with the results from the EU WTW study, with all cases showing considerable potential for decreased CO_2 emissions.

In *Paper II*, the results shows that BMG could have potential to contribute to reduced global CO_2 emissions. Here, the CO_2 effects of introducing BMG in the Linköping DH system have also been evaluated using the more comprehensive approach where biomass is regarded as limited[26]. The original as well as the new results are shown in Figure 19, with biomass regarded as limited (filled columns), and as CO_2-neutral (hatched columns). As discussed in Section 6.1, investment in biofuel production is profitable in all scenarios when a biofuel policy support is applied (green columns). With no biofuel policy support (blue columns), two scenarios (2 and 4) contains no BMG investments, while BIGCC is the preferred technology in scenarios 1 and 3.

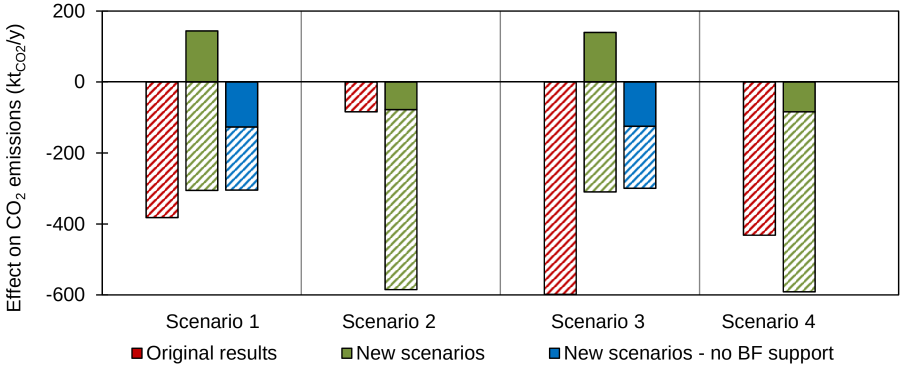

Figure 19: Effect on CO_2 emissions for the Linköping DH system, when considering marginal CO_2 effects of biomass (filled columns), and when regarding biomass use as CO_2 neutral (hatched columns), compared to the respective reference scenario. Original results from Paper II (old scenarios), as well as updated results using the new scenarios (with and without biofuel policy support).

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[26] On the new results using the Paper IV/V scenarios, as described in Section 6.1.

When moving from a simplified to a comprehensive CO_2 analysis, it is clear that implementation of BMG in the DH system does not necessarily entail a potential for reduction of CO_2 emissions. With biofuel production in the system, the CO_2 emissions are only reduced in two scenarios (2 and 4), compared to the corresponding reference scenario. The reason for the decrease is that the marginal electricity production in those scenarios is low-emitting (coal with CCS), which makes the emissions in the reference scenario (with biomass CHP) higher. In scenarios 1 and 3, electricity from the reference biomass CHP plant replaces coal power, which gives a higher CO_2 reduction effect than the fossil transport fuel displaced by produced SNG. With BIGCC in the system (scenarios 1 and 3 without biofuel policy support), the electricity production is always higher than in the reference scenario, which leads to a decrease in CO_2 emissions.

The original results show a much larger variance between the scenarios. The main reason is that in the original results more than one investment could be made in the system, which gives more diversified production mixes between the scenarios. Also, the old scenarios include three different marginal electricity production technologies (coal, coal with CCS, and NGCC), instead of only two, as in the new scenarios.

The results from *Paper IV* are shown in Figure 20. The effects of integration of BMG in the pulp and paper mill have been evaluated both in relation to the original mill alone (red columns), and in relation to the mill and a stand-alone BMG plant in combination (green columns). The results for only the stand-alone BMG plants are also included (blue columns).

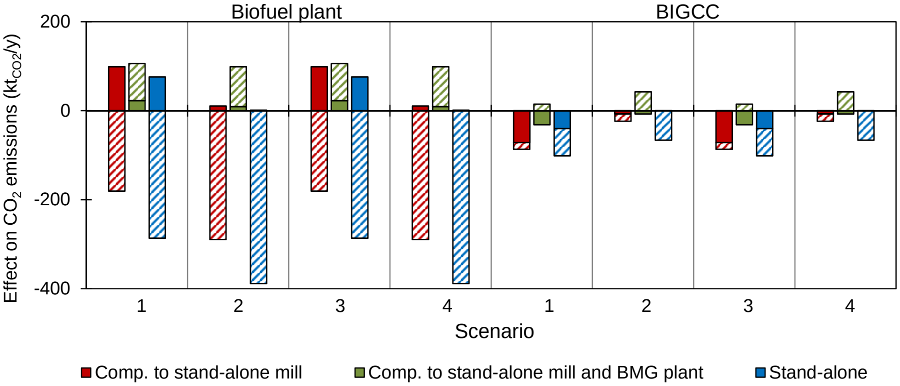

Figure 20: Effect on CO_2 emissions for the Billerud Karlsborg pulp and paper mill, when considering marginal CO_2 effects of biomass (filled columns), and when regarding biomass use as CO_2 neutral (hatched columns).

Also here, the CO_2 reduction potential of implementation of large-scale BMG is shown to be far from certain. In fact, when marginal effects of biomass are considered, none of the biofuel cases show any reduction potential at all. The main reason is the large amount of biomass needed for the biofuel production plants.

The emissions from displaced fossil fuels and from alternative DH production (in the stand-alone case), are not enough to offset the indirect emissions related to the alternative biomass use. When regarding biomass use as CO_2-neutral, BMG with biofuel production leads to decreased CO_2 emissions in the stand-alone case, and for the biorefinery when using only the mill as reference. However, when comparing the DME biorefinery to the complete stand-alone case, the CO_2 emissions instead increase. The reason is that when including the stand-alone case in the comparison, the credit for displaced fossil DH heat in the stand-alone plant leads to an apparent increase for the biorefinery.

The BIGCC cases in general show some potential for decreased CO_2 emissions, also when considering the marginal effects of biomass use. This is particularly evident in the scenarios with high-emitting marginal electricity production (scenarios 1 and 3), due to the high electrical efficiency of the combined cycle.

Papers *VI-VII* have also employed a simplified CO_2 analysis, since CO_2 analysis is not the primary aim of the papers. The analysis includes CO_2 emissions from the transport of biomass and biofuels, as well as offset emissions from displaced fossil energy carriers. The results from Paper VI for all studied scenarios are shown on the left-hand side of Figure 21. Since the assumed reference system is all fossil, all scenarios show a potential for decreased CO_2 emissions. Unsurprisingly, an increasing biofuel share entails an increasing emission reduction potential. This is more significant in scenarios where ethanol plants dominate than in scenarios where methanol plants do. The reason is the higher conversion efficiency to electricity and heat in the ethanol plants, in combination with the in general significantly higher CO_2 emission factors of displaced electricity and heat compared to displaced fossil transport fuels. Consequently, a considerable part of the reduced CO_2 emissions in the ethanol-dominated scenarios can be attributed to the co-products.

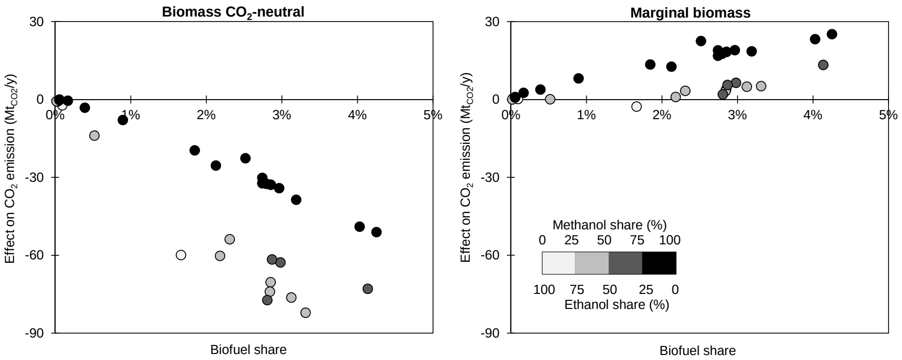

Figure 21: Effect on CO_2 emissions related to biofuel share in the EU when regarding biomass use as CO_2 neutral (left), and when considering marginal CO_2 effects of biomass (right). The shade of the markers indicates whether a scenario is dominated by methanol or ethanol plants.

The right-hand side of Figure 21 illustrates the impact of the assumption that biomass use is neutral, by showing a hypothetical CO_2 effect if all biomass used were to be penalised with CO_2 emissions of the assumed alternative biomass usage (co-firing with coal in power plants). In line with the results discussed previously in this section, the CO_2 emissions would now increase rather than decrease, with an increasing biofuel share. In fact, only one scenario (dominated by ethanol) shows any CO_2 mitigation potential. However, if the model was to actually be run with a CO_2 emission factor for biomass equivalent to coal combustion, the optimal solutions would not contain the number of biofuel production plants resulting in the biofuel shares shown in the figure, since the CO_2 emissions are internalised in the objective function of the model.

Since the systems studied for this thesis are of very different size, the resulting CO_2 emissions can not be directly compared quantitatively. As discussed in Section 5.1.1 and in Paper I, the results should be reported per unit of biomass used or per land area used for biomass production, when different systems are compared. Since the same type of biomass feedstock has been used in all studied systems, reporting per biomass unit is suitable. Figure 22 shows an illustrative example of the resulting CO_2 emissions per unit of biomass, for the systems studied in this thesis. The reference system applied for the figure encompasses electricity produced in coal power plants, biomass CHP as alternative DH heat production and biofuel use in hybrid vehicles. The results are shown both for when considering marginal effects of biomass use, with co-firing with coal in power plants as marginal biomass user, and when regarding biomass use as CO_2-neutral.

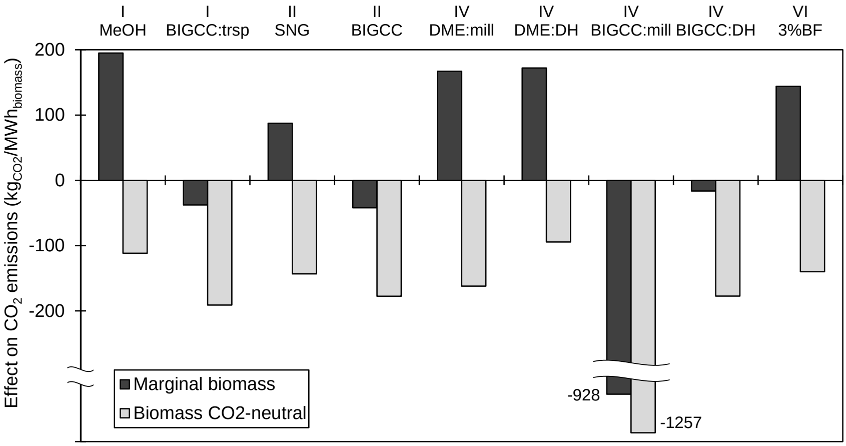

Figure 22: CO_2 effect per unit of biomass for the systems studied for this thesis, when considering marginal CO_2 effects of biomass as well as when regarding biomass use as CO_2-neutral. Electricity produced in BIGCC is assumed to be delivered to the grid in all cases, except for in the Paper I case (BIGCC:trsp), where it is assumed to be used in battery-powered electric vehicles. MeOH = methanol, 3%BF = scenario from Paper VII reaching a 3% biofuel share in the EU (36 EUR/MWh biofuel support).

From the figure it is clear that unless biomass use is regarded as CO_2-neutral, none of the biofuel cases show any potential for CO_2 emission reduction. SNG performs best of the biofuels, which can largely be attributed to the higher co-production of heat. On the other hand, all BIGCC cases show some reduction potential, irrespective of whether the produced electricity is assumed to be used in transport or exported to the grid. It should be noted that only the case of regarding coal power as marginal electricity has been illustrated here. The case of BIGCC integrated with the mill shows outstanding emission reduction potential, if compared to the other cases. This is due to the fact that in the results shown here the BIGCC plant is compared only to the original mill. With only a relatively small addition of biomass, a very high additional electricity production can be achieved, when moving from a boiler-based steam turbine system, to a gasification-based combined cycle system. This shows that integration is important in order to use limited biomass resources efficiently.

7
Concluding remarks

This final chapter begins with a discussion associated to the studies performed in this thesis, which is followed by conclusions in relation to the posed research questions, as well as some general conclusions. The chapter ends with suggestions for further work.

7.1 Discussion

This thesis has aimed at performing systems analyses of integration of large-scale forest biomass-based BMG applications with other parts of the energy system. This has been done both from a techno-economic perspective, and regarding effects on global CO_2 emissions.

The results from this kind of study, with many assumptions and a large number of exogenous variables with a high degree of uncertainty, are naturally highly sensitive to the applied input data. In particular, input data regarding future energy market conditions and plant investment costs have been shown to have a large effect on the results. In the studies for this thesis, techno-economic data from the literature has been used for the studied BMG technologies. This has been found to be problematic, since different sources have often applied different assumptions and used different time frames. To account for this, separate literature sources have been compared, and adjustments have been made in order to accommodate for variation in assumptions and base data. However, when analysing the results, it has been found that even relatively small changes in, for example, assumed efficiencies or investment costs may have a large impact on the results.

In five of the papers the choice was made to use optimisation models for the systems analysis. For the Linköping DH system (Papers II-III) optimisation was a logical choice, due to the complexity of the system. The investment opportunity could have been investigated using a spreadsheet model, but this would have removed the possibility of analysing effects, for example, on the dispatch order and annual operating time of different heat production facilities. For the Billerud pulp and paper mill (Paper V), the analysis could also have been done without an optimisation model, but here the model was partly constructed to be used in further studies, including other biorefinery options (not yet published). One problem with optimisation models like those used for this thesis, is that they are based on “perfect foresight”, which means that the future energy market conditions are known by the model at the time of investment. One way to counter this could be to use optimisation under uncertainty, which, however, is more complicated regarding input data, as probability functions for various parameters are required.

Regarding energy market conditions it is obviously impossible to make certain predictions for the future. For this reason, it is important to illustrate the influence of several different future energy market conditions. In four of the seven papers of this thesis, energy market scenarios with interdependent parameters have been used. The scenarios take into consideration the strong connection between different energy market parameters, and as such enable a form of packaged sensitivity analysis. In the papers on biofuel production on a European level (Papers VI-VII), a simplified approach was used, applying current energy prices and conducting sensitivity analysis of one parameter at a time. The reason for using this approach was that the model used is still at the development stage, where it is important to gain knowledge about model response to various changes in input, in order to be able to calibrate the model for more advanced scenario analysis in future work.

Several of the papers have focused on policy support in the form of economic support for biofuels, or electricity certificates, with the Linköping study also including energy taxation. The reason for including this in only one study was that for a DH supplier utilising a relatively large amount of fossil fuels, taxes play a significant role. During the work for Papers II and III, sensitivity analysis (not published) was made with the taxes removed. Since the new biomass-based investments were shown to cover a large part of the annual heat demand, with only winter peak demands met by fossil fuels, removal of the taxes turned out to have little effect on the results.

Regarding the CO_2 analysis, three of the five papers that included evaluation of the effect on global fossil CO_2 emissions applied a simplified approach, where biomass use was considered CO_2-neutral. The main reason for not applying the more comprehensive approach that was used in the other two papers was that in-depth CO_2 evaluation was not the main focus of those papers. The simplified CO_2 analysis applied was viewed as a preliminary screening of the CO_2 reduction potential. However, the results from the extended analysis performed for this thesis clearly shows that if the marginal effects of use of limited biomass resources are not considered, the CO_2 effects of implementation of large-scale biomass using systems, such as BMG technology, may be severely underestimated. In a model such as the BeWhere EU model, marginal CO_2 effects can be included by extending the model to also encompass alternative biomass use, in the form of existing biomass users such as industry and biomass CHP, as well as potential marginal users, such as coal power plants. When doing this, the effects of an increasing CO_2 cost on the marginal biomass use can be more closely analysed, as at low CO_2 costs, co-firing with coal can be expected to be less attractive than at high costs. If coal power plants would in this way be regarded explicitly as potential biomass users, the somewhat unconventional assumption that biomass should have a CO_2 emission factor equivalent to that of coal would also be more easily accounted for. By including alternative biomass use, issues regarding competition can also be addressed explicitly.

Further, in the EU biofuel studies, static CO_2 emission factors of displaced fossil energy carriers were used. This means that the same emission factor, for example of displaced electricity, was used at high as well as at low CO_2 costs. If implementing scenarios with interdependent parameters, similar to those used in Papers II-V, emission factors as well as energy prices would change with an increasing CO_2 price, which would affect the results, in particular regarding biofuels with high co-production of other energy carriers.

The papers have applied different system perspectives and used different starting points. In the detailed DH system study (Papers II-III), the study was made from the DH supplier's point of view. There the aim was to meet a certain heating demand, at the lowest possible cost. This made the BMG alternatives economically interesting, since another rather high-cost alternative (conventional biomass-based CHP) was used as reference technology. Conversely, Paper IV applied an industrial perspective for the stand-alone BMG plant delivering heat to a DH network, where heat was valued according to an assumed alternative heat production cost. The difference in results between the two starting points verify that due to the very local nature of DH systems, it is important to carefully consider the detail level needed when performing systems analyses involving DH systems.

The analyses in this thesis have been made from two directions. In parts of the thesis a bottom-up approach with detailed case studies has been applied, with simplifications of the surrounding systems. In other parts a more top-down approach has been applied, with analysis on a European level and considerable aggregation of system-specific properties. When (or if) second-generation biofuel production reaches commercial operation, the plants will likely need to be large to reach necessary efficiencies and economies of scale. Large plant sizes increase the necessary feedstock supply area and put significant demands on the supply chain, which makes it necessary to carefully choose the geographic location of the production plants with respect to fuel demand and feedstock locations. Co-production of additional energy carriers, such as heat, lignin or electricity, gives an opportunity for higher total conversion efficiencies, but also puts additional requirements on the determination of the optimal biofuel production plant locations. Further, existing biomass users, for example forest industry or CHP plants, affect the local and regional availability of biomass feedstock. With knowledge gained in detailed case studies, such as those performed in this thesis, qualified geographically explicit systems analyses can be performed in order to evaluate sites of interest.

A broad introduction of large-scale BMG technology could lead to a high stress on the available resources of forest biomass, as the biomass demand would increase significantly. If the objective is to maximise the CO_2 mitigation effect per unit of biomass, coal replacement will always be the winning alternative. However, if other renewable alternatives for heat and electricity were to constitute the base of a future energy system, more biomass could be accessible for BMG-based biofuel production, with a lower marginal effect per unit of biomass used. In the studies for this thesis, different assumptions have been made regarding biomass availability. In the two Swedish case studies, it was assumed that the local/regional biomass supply would be sufficient, with no geographically explicit considerations being made. In the EU study geographical forest data was included. However, when modelling the assumed availability and costs of forest biomass, the current status of forestry technology was not taken into account. While countries such as Sweden, Finland and Austria already have a well-developed system for recovering forest residues from final felling and thinning, this system is considerably less developed in, for example, Spain.

7.2 Conclusions

1. Can investment in large-scale biomass gasification technology be an economically attractive option for integration with ...

(a) ... district heating?

(b) ... pulp and paper production?

For the systems studied in this thesis, the potential of integration with other energy systems can be concluded to provide incentives to make large-scale BMG applications economically interesting. BMG-based biofuel production has been shown to perform well in the studied district heating systems, as well as in the pulp and paper mill, while BIGCC was shown to perform significantly better when integrated with a pulp and paper mill than with district heating.

It can also be concluded however that the economic attractiveness of BMG is highly sensitive to several parameters. The most profound such parameter is the need for economic policy support, without which large-scale biomass gasification does not show much promise to become economically attractive. Capital costs, heat revenues, and feedstock costs in relation to the sell price of biofuel or electricity also constitute determining parameters.

2. What levels of economic policy support are needed to make investments in biomass gasification technology economically attractive?

It can be concluded that the levels of policy support needed to make investments in BMG attractive are very much dependent on other energy market conditions, in particular the price relation between different energy carriers and the market oil price. With low oil prices, the needed biofuel support ranges from levels comparable to current biodiesel tax exemptions in the EU, to a level higher than even the current ethanol tax exemptions. High oil prices would suppress the need for policy support considerably. The important conclusion from this is not the actual levels of support needed, since those are strongly dependent on the study-specific assumptions made, but that in the current system considerable support is needed – unless oil prices are high. As mentioned in the Background (Section 2.3), global subsidies to fossil fuels are today almost an order of magnitude higher than global subsidies to biofuels. Simultaneously, the marginal damage costs of CO_2 emissions are today not fully manifested in fossil fuel prices. If fossil fuels were to carry all the costs associated with their use, this would be reflected in the level of policy support needed for renewable energy.

Competition with high-cost conventional technology, such as biomass-fired CHP, naturally reduces the need for support. For BMG-based electricity production via BIGCC, the sensitivity to the assumed energy market conditions was concluded to be even higher than for biofuel production. The needed support for BIGCC in the studied district heating system, with the assumed electricity prices, would range from levels comparable to the current policy support for biomass-based electricity in many EU countries, to levels significantly higher than today's support levels.

3. What could be suitable locations for future large-scale biomass gasification plants?

District heating systems can provide heat sinks for excess heat from large-scale BMG plants, which would increase the overall conversion efficiency and reduce the need for primary energy. From a district heating supplier's point of view, the revenue from high-value energy products (biofuel or electricity) can lead to low heat production costs. From a BMG plant operator's point of view, the extra revenue for heat sold to a district heating network would instead reduce the biofuel or electricity production costs. Thus, it can be concluded that district heating systems are of interest when considering locations for future BMG plant locations. Similarly, integration with pulp and paper mills with a heat deficit can provide suitable locations, with the heat from the BMG process reducing the need to burn extra fuel for steam production.

On a larger geographical scale, it can be concluded that BMG plants would optimally be located close to where there is high availability of low-cost forest residues. For the EU this would mean that biofuel should be produced in the forest-rich northern parts (Sweden, Finland and the Baltic states), as well as in northern Spain, where the annual growth is high. However, to be able to utilise forest residues in Spain, for example, significant development on the forestry side would be needed.

4. How would implementation of large-scale biomass gasification technology affect global fossil CO_2 emissions?

Implementation of large-scale BMG does not necessarily entail a reduction of global fossil CO_2 emissions. In fact, when considering the marginal CO_2 effects of increased biomass use, most BMG-based biofuel cases studied in this thesis would lead to an increase rather than a decrease of CO_2 emissions. BMG-based electricity production in the form of BIGCC shows more potential for CO_2 emission mitigation, due to the high electrical efficiency and the higher emission factor per unit of biomass of displaced electricity, compared to displaced transport fuel. This is particularly noticeable with a high-emitting marginal electricity production technology, such as coal power.

From the results of the papers, in combination with the extended analysis performed here, it can be concluded that it is important to take into account the fact that biomass will in the near future be a limited resource. Failure to expand the system to take alternative biomass use into account may result in overestimation of the potential of biomass-using systems to contribute to reduced CO_2 emissions. This is particularly important when evaluating emerging technologies, such as BMG, that can be expected to use a substantial amount of the available biomass resources, which may have as a consequence that demand from other applications must instead be met by fossil fuels.

General conclusions

- Large-scale biomass gasification for biofuel or electricity production may constitute economically interesting alternatives for integration with district heating systems or pulp and paper production in the future, *but* ...
- ...the economic attractiveness is sensitive to a number of assumptions, in particular regarding energy market conditions and investment costs.
- Due to the large capital commitment of investment in biomass gasification technology, and the high dependency on a number of external factors, forceful economic support policies will be needed if biomass gasification is a desired route for the future energy system, *unless* ...
- ...the oil and electricity prices are high enough to provide sufficient incentives for biomass gasification-based biofuel and electricity production.
- When acknowledging the marginal effects of biomass as a limited resource, the CO_2 mitigation potential for biomass gasification-based biofuel production becomes highly uncertain.
- In order to utilise limited biomass resources efficiently, integration of large-scale biomass applications is important.
- In order to reach the EU targets for renewable energy and biofuels, further interdisciplinary energy system studies will be needed. A geographically explicit model such as the one used in parts of this thesis, in combination with knowledge gained from detailed case studies, could constitute a key component for these kinds of studies and be highly relevant for policy makers.

7.3 Further work

The work presented in this thesis was limited to two system case studies of local character, and an aggregated system study on the European level. In order to more fully be able to make conclusions about which locations might be suitable for future large-scale bioenergy conversion facilities, it would be interesting to complement the systems studies performed here with studies lifted from the case study level, but narrowed down from the European level. Regions or countries appear to be suitable levels for this type of study, as it would be possible to make more specific assumptions, while at the same time maintaining a perspective larger than a single district heating system or industry. Further, the types of systems studied here could be complemented with other system types, to broaden the integration potential. An example is district cooling which, if supplied by heat-driven absorption cooling, can provide a heat sink in areas where the demand for district heating is low or non-existent.

As a complement to techno-economic studies of the kind presented in this thesis, which analyse future energy systems by using the present system as a starting point, studies using a back-casting approach could also be used. By using a desired future system as starting point, the factors that were shown to introduce large uncertainty (for example investment costs and energy market conditions) can be handled.

There is also a need for continued development of consistent energy market scenarios with interdependent parameters. Those scenarios could be founded in national or supranational road maps and policies, and should include both alternatives where biomass is a limited resource subject to competition, and alternatives where the energy sector is to a larger extent supplied by other renewable alternatives. The CO_2 analysis could also be complemented with soil carbon dynamics and land-use change effects, direct as well as indirect.

Spatially explicit optimisation models constitute tools suitable for cross-sector system studies. Areas of interest for further development of the model used in this thesis include competition for biomass resources from other sectors, addition of biomass resource types other than forest biomass, and introduction of biomass prices as endogenous variables, to account for market effects when utilising large shares of the available resource. Further, integration of biofuel production with industry could be included in the model, as could the heat and power sectors.

On the technology side, this thesis has focused on biomass gasification. In future work, the scope should be widened to include additional competing technologies, biomass based as well as non-biomass based. Further, improved quality and availability of technology data would improve this kind of system study significantly. Future studies should also be broadened to also put more consideration on the transport sector, in order to account for other transport alternatives.

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