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Industrial Symbiosis in the Biofuel Industry:

Quantification of the Environmental Performance and Identification of Synergies

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Cover Art

The cover of this thesis was designed to depict the connection between a natural ecosystem and an industrial system. A natural ecosystem is depicted on the bottom as the benchmark for sustainable systems. An industrial symbiosis network and agricultural system are shown above it, with symbiotic connections to optimize material and energy flows in an attempt to model natural ecosystems and move the system toward environmental sustainability. Connections can be seen between the plants, as well as possible connections (depicted with dashed lines), to depict the synergies.

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Abstract

The production of biofuels has increased in recent years, to reduce the dependence on fossil fuels and mitigate climate change. However, current production practices are heavily criticized on their environmental sustainability. Life cycle assessments have therefore been used in policies and academic studies to assess the systems; with divergent results. In the coming years however, biofuel production practices must improve to meet strict environmental sustainability policies.

The aims of the research presented in this thesis, are to explore and analyze concepts from industrial symbiosis (IS) to improve the efficiency and environmental performance of biofuel production and identify possible material and energy exchanges between biofuel producers and external industries.

An exploration of potential material and energy exchanges resulted in a diverse set of possible exchanges. Many exchanges were identified between biofuel producers to make use of each other's by-products. There is also large potential for exchanges with external industries, e.g. with the food, energy and chemical producing industries. As such, the biofuel industry and external industries have possibilities for potential collaboration and environmental performance improvements, though implementation of the exchanges may be influenced by many conditions.

In order to analyze if concepts from IS can provide benefits to firms of an IS network, an approach was created which outlines how quantifications of IS networks can be produced using life cycle assessment literature for guidelines and methodological considerations. The approach offers methods for quantifying the environmental performance for firms of the IS network and an approach to distribute impacts and credits for the exchanges between firm, to test the assumed benefits for the firms of the IS network.

Life cycle assessment, and the approach from this thesis, have been used to quantify the environmental performance of IS networks by building scenarios based on an example from an IS network of biofuel producers in Sweden. From the analyses, it has been found that exchanges of material and energy may offer environmental performance improvements for the IS network and for firms of the network. However, the results are dependent upon the methodological considerations of the assessments, including the reference system, functional unit and allocation methods, in addition to important processes such as the agricultural inputs for the system and energy systems employed.

By using industrial symbiosis concepts, biofuel producers have possibilities to improve the environmental performance. This is done by making use of by-products and waste and diversifying their products, promoting a transition toward biorefinery systems and a bio-based economy for regional environmental sustainability.

Sammanfattning

Produktionen av biobränslen har ökat de senaste åren, vilket är ett steg mot klimateffektivare lösningar i transportsektorn, men biodrivmedlen har ifrågasatts med hänvisning till tveksamheter kring deras miljö- och energiprestanda. Lifecykelanalyser har därför använts inom akademiska studier och för policy för att utvärdera systemen, dock utan samstämmiga resultat. Under de kommande åren måste därför praxis för produktion av biobränslen förbättras för att kunna möta de strikta kraven i hållbarhetskriterier för biobränslen.

Syftet med forskningen som presenteras i den här doktorsavhandlingen är att utforska och analysera koncept från området Industriell symbios (IS) och därigenom identifiera förbättringar för ökad effektivitet och miljöprestanda för biobränsleproduktion. Vidare är syftet att identifiera möjliga material- och energiutbyten mellan biobränsleproducenter och externa industrier.

Potentiella material- och energiutbyten undersöktes, vilket resulterade förslag på flera olika typer av potentiella utbyten. Undersökningen visar på en potential för att använda biprodukter i en biobränsleprocess som råvara till en annan biobränsleframställning. Vidare identifierades en stor potential för utbyten med externa industrier, som till exempel matproducenter samt industrier för energi och kemikalier. Det är tydligt att det finns möjligheter för biobränsleproducenter och externa industrier att samarbeta och därmed ge möjlighet till förbättringar i miljöprestandan, dock kan en implementering av dessa utbyten påverkas av många olika förutsättningar.

Avhandlingen presenterar även ett tillvägagångssätt för att visa hur kvantifiering av miljöprestanda inom ett nätverk för IS kan genomföras genom att använda riktlinjer och metodavvägningar från litteratur för livscykelanalys. Detta tillvägagångssätt kan användas för att analysera om koncept från IS kan leda till fördelar för företagen i ett IS-nätverk.

Tillvägsgångssättet ger möjlighet att kvantifiera miljöprestandan för företagen i IS-nätverket och ger dessutom vägledning för hur miljöpåverkan från utbytena kan distribueras mellan de olika företagen. Metoden utvecklades för att bland annat undersöka de förmodade fördelarna från IS för varje enskild aktör.

Livscykelanalys i kombination med tillvägagångssättet ovan har använts för att kvantifiera miljöprestandan för IS-nätverk genom att konstruera scenarier. Scenarierna har baserats på ett exempel från ett IS-nätverk av biobränsleprocenter i

Sverige. Analyserna visar att utbyten av material- och energi kan ge förbättringar i miljöprestanda. Resultaten är dock beroende av vilka metodavvägningar som gjorts, till exempel val av referenssystem, funktionell enhet och allokeringsmetoder. Vidare spelar viktiga processer som inputs från jordbruk och val av energisystem stor roll för resultatet.

Metodavvägningar för utväderingen influerar även miljöpåverkan samt hur den fördelas mellan företagen i IS-nätverket. Dessutom kan den lokala miljöpåverkan öka medan den globala påverkan minskar.

Sammanfattningsvis kan biobränsleproducenter, genom att använda koncept från industriell symbios, ges möjlighet att förbättra sin miljöprestanda. Detta kan ske genom att använda biprodukter och avfall samt genom att diversifiera sina produkter som ett första steg mot en övergång mot bioraffinaderier och en mer biobaserad ekonomi för regional hållbarhet.

Acknowledgements

This research was conducted under the guidance of Professor Mats Eklund and supervisor Niclas Svensson, for whom I would like to extend my sincere gratitude for the invaluable support, ideas, discussions and contributions to this work and in my own development as an academic.

Gratitude is owed to Magnus Karlsson from the Division of Energy Systems for his reviews, remarks, comments and suggestions to raise the level of this thesis and final appended papers. Furthermore, I would like to thank the anonymous reviewers for their comments, ideas and guidance in the production of the appended papers.

I would also like to thank the employees of Svensk Biogas, Tekniska Verken, Agroetanol, the former Ageratec, Swedish Biogas International and E.ON for answering my many questions and providing data necessary for quantifications.

My special thanks are extended to the staff of Environmental Technology and Management for the twice daily *fika* breaks, at precisely 9:30 and 14:30. The breaks provided well needed caffeine breaks, sugar "top-ups," interesting discussions related to the research and other topics not the least job related, usually ending with videos being sent from YouTube, during the writing process.

I would like to express my deepest appreciation to Sofia Lingegård for her support, inspiration and understanding during the years to produce this thesis, especially during the last few weeks. Nívós, my dog, also deserves gratitude for always being happy to see me when I get home, allowing me to realize a balance between life and work is needed when writing a thesis and sharing many adventures with me.

Finally, I would like to thank my family for their support, understanding and care packages sent "across the pond" when the odd American craving came about or new hunting or fishing equipment was needed.

Appended Papers

Paper I
Martin, M. & Eklund, E., 2011. Improving the environmental performance of biofuels with industrial symbiosis. Biomass and Bioenergy 35(5), 1747-1755.

Paper II
Martin, M., Svensson, N., Eklund, E. & Fonseca, J., 2012. Production synergies in the current biofuel industry: Opportunities for development. Biofuels 3(5), 545–554

Paper III
Martin, M., Svensson, N., Fonseca, J. & Eklund, M. Quantifying the environmental performance of integrated bioethanol and biogas production. Renewable Energy, In Press, Corrected Proof. DOI: http://dx.doi.org/10.1016/j.renene.2012.09.058

Paper IV
Martin, M., Svensson, N. & Eklund, M. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. Manuscript. Selected and Submitted for Special Issue, Journal Cleaner Production from the Greening of Industry 2012 Conference, "Support your future today."

Paper V
Martin, M. Using LCA to quantify the environmental performance of an industrial symbiosis network: Application in the Biofuels Industry. Manuscript.

My Contribution to Articles

Paper I- Major contribution for data collection and writing.

Paper II- Major contribution for data collection and writing.

Paper III- Major contribution for writing and shared contribution for data collection.

Paper IV- Major contribution for data collection and writing.

Paper V- Exclusive contributor for data collection and writing.

Related Publications

Martin, M. & Parsapour, A. Upcycling wastes with biogas production: An exergy and economic analysis. Conference Paper for Venice Symposium 2012, Fourth International Symposium on Energy from Biomass and Waste, Venice, Italy. Selected and Submitted for Special Issue of Waste Management, February 2013.

Martin, M., Svensson, N., Fonseca, J. & Eklund, M., 2012. Quantifying the environmental performance of integrated bioethanol and biogas production. Linköping University -IEI Report Number: LIU-IEI--10/0092--SE.

Martin, M., & Fonseca, J., 2011. A systematic literature review of biofuel synergies Linköping University -IEI Report Number: LIU-IEI-R--10/0092—SE.

Martin, M., Ivner, J., Svensson, N., & Eklund, M., 2009. Biofuel synergy development: Classification and identification of synergies using industrial symbiosis. Linköping University-IEI Report Number- LIU-IEI-R--09/0063—SE.

Nomenclature

Listed below are some of the common acronyms and compounds used in this thesis

CHP	Combined Heat and Power
DDGS	Dried Distillers Grains with Solubles
EA	Energy Allocation Method
ESA	Environmental Systems Analysis
EU-RED	European Union-Renewable Energy Directive
GJ	Gigajoule(s)
GWP	Global Warming Potential
IS	Industrial Symbiosis
LCA	Life Cycle Assessment
SE	System Expansion Method

CO_2	Carbon Dioxide
CH_4	Methane
PO_4	Phosphate
SO_2	Sulfur Dioxide

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"There is an old African proverb that says if you want to go quickly, go alone, if you want to go far, go together. We have to go far, quickly, and that means we have to quickly find a way to change the world's consciousness about exactly what we are facing and how we have to work to solve it."

-Al Gore

Thesis Outline

Chapter 1 of this thesis provides an introduction to research conducted for this thesis and outlines the aims, scope and limitations. Thereafter, an overview of the papers is provided through the research journey, which describes the research process used to complete this thesis.

Chapter 2 will provide the reader with a background on the production of biofuels, outlining the production processes, policies and promotion of biofuels as a substitute for fossil fuels.

Chapter 3 describes the theories and concepts used in this thesis to give the reader an introduction to industrial symbiosis, life cycle assessment and previous research in the areas related to this thesis. Included in the descriptions are also the limitations of the theories and methods, which will be reviewed again in the methodology chapter. The chapter ends with a position on how the theories are used in this thesis.

Chapter 4 will provide a review and motivation for the methods and approaches used in this thesis.

Chapter 5 presents the industrial symbiosis network of Händelö and the scenarios used in the quantifications for the appended papers.

Chapter 6 provides a summary of the identified synergies between the biofuel and external industries.

Chapter 7 outlines the approach produced to quantify industrial symbiosis networks.

Chapter 8 provides results from the appended papers for environmental performance quantifications.

Chapter 9 offers a discussion of the results from the thesis.

Chapter 10 provides a reflection from this work on the possibilities for biofuels to promote a transition to a bio-based economy.

Chapter 11 summarizes the work and answers the research questions based on the results and discussion.

Chapter 12 offers reflections on possible future research.

1 Introduction

This section will provide a background and introduction to the thesis. Thereafter, the aims and scope will be reviewed along with a "journey" of this research project through the appended papers.

Since the dawn of industrial development, the consumption of natural resources has increased at an unprecedented rate to fuel growth worldwide. Energy use, in particular fossil fuels, has followed this trend, producing equivalently large environmental impacts[1] and emissions of greenhouse gases. Nations worldwide have thus set forth actions to reduce their environmental impacts through policies aiming to diversify the energy supply and decouple the dependence on fossil fuels. In the transportation sector, biofuels[2] have been promoted as one option to reduce the dependence on fossil fuels, and policies are in place to promote their use through blending obligations and tax exemptions for producers and users (European Union, 2009b).

Despite the widespread promotion of biofuels worldwide, biofuels have been criticized heavily in recent years. The criticism includes debates on the competition with food crops, land availability and energy requirements for production practices (Ponton, 2009; Timilsina and Shrestha, 2011). In order to assess the sustainability of biofuel production, many have turned to assessments of the greenhouse gas emissions from biofuel production, therefore numerous life cycle assessments (LCA) have been conducted worldwide.

From the results of the LCAs, biofuel production has been portrayed on a whole spectrum of outcomes; i.e. from being extremely beneficial to those studies showing biofuel production as a threat to the environment (Gnansounou et al., 2009). Methodological considerations, such as the assumptions made, methods, energy systems, allocation procedures and other aspects related to the life cycle assessment in addition to contextual differences have resulted in these divergent results (Cherubini, 2010b; van der Voet et al., 2010). Therefore, it is not easy to say whether

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[1] ***Environmental impacts***- refer to impacts to the environment in several categories. This can include global impacts, such as global warming potential as well as local impacts, including acidification, eutrophication, etc.

[2] ***Biofuels***- will be referred to in this thesis as fuels produced for transportation purposes derived from crops and wastes. These fuels are typically delivered in gaseous or liquid state and do not include biomass. Biofuels will be used in this thesis to denote commercially available biofuels, including biogas, biodiesel and bioethanol, and not advanced biofuels unless otherwise specified (International Energy Agency, 2005; Worldwatch Institute, 2006).

biofuel production processes are "good or bad," and according to Börjesson (2009) depends upon many factors for the assessments, including the handling of by-products, energy systems used and extent to which environmental impacts from the use of raw materials are included.

Despite the criticism and strive for improvements, biofuels continue to be promoted by governments and currently a large number of commercial biofuel plants are operational worldwide. Policies have also addressed the environmental performance with strict mandates for greenhouse gas reductions compared to fossil equivalents, with even stricter targets in the coming years (European Union, 2009b). It is important to look therefore to improve many of these systems, by improving the environmental performance[3] and energy efficiency. Integration to promote the use of by-products and wastes, linking by-product and utilities streams using concepts from industrial symbiosis (IS) may offer improvement potential. Exchanges and integration may take place between any number of industries, depending upon the biofuel. Many exchanges have been found within the biofuel industry[4], thus moving current biofuel systems more toward biorefinery concepts. An example of such exists on the island of Händelö in Norrköping, where a biogas, ethanol and CHP plant collaborate. Additionally, a large potential is found outside the biofuel industry to handle by-products from industrial and agricultural processes.

In the literature, the underlying consensus from many studies is that industrial symbiosis "should" lead to mutual benefits for companies involved in the exchanges; though it is uncertain whether IS essentially leads to benefits. Hitherto, only a few quantifications of industrial symbiosis networks are available. Those which quantify IS networks typically review a selected few exchanges or quantify the entire IS network (Wolf and Karlsson, 2008; Mattila et al., 2010; Sokka et al., 2011). The results include material consumption reductions or entire IS network impacts. In several of the studies, a reference system is compared with an existing IS network or proposed changes. However, the choice of the reference system may be influential for the results (Karlsson and Wolf, 2008; Wolf and Karlsson, 2008; Sokka, 2011). Moreover, these studies may not entirely capture the environmental impacts present. Therefore, it is important to show the impacts and benefits for individual

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[3] ***Environmental performance-*** refers the environmental impact of the process being assessed. Processes having a "good" environmental performance are those seen to have low impacts, while those with "bad" environmental performance are those with large impacts. See the footnote on environmental impacts.

[4] ***Biofuel industry***-will refer to biofuel producers in general, including biogas, biodiesel and ethanol production plants.

firms of the symbiosis network as traditionally industrial symbiosis aims to create "win-win situations" for all firms involved (Chertow, 2000). In order to add transparency to the quantifications, the IS field may benefit from the use of LCA to provide guidelines on how to quantify the impacts from industrial symbiosis networks (Mattila et al., 2010; van Berkel, 2010; Mattila et al., 2012). Nevertheless, tools from industrial ecology, such as life cycle assessment, are rarely applied for industrial symbiosis quantifications, as there is a general lack of quantifications (Wolf and Karlsson, 2008).

As the biofuel industry looks to develop and improve its environmental sustainability, new approaches to the production processes must be explored. Integration with external industries and exchanges of material and energy may offer potential routes for the biofuel industry to obtain new feedstocks, increase valorization of products and improve the environmental performance (Murphy and Power, 2008; Börjesson, 2009). Furthermore, by bridging industrial ecology and life cycle assessment, quantifications may be used to assess the possibilities of exchanges to improve the biofuel industry and offer the industrial symbiosis community further insight into methods for quantifying industrial symbiosis networks.

1.1 Aims & Objectives

The aim of this thesis is to provide support for the development of more resource efficient biofuel production systems by exploring and analyzing concepts from industrial symbiosis through the exchanges of material and energy. Furthermore, this thesis aims to understand how the quantifications may be undertaken in order to provide an approach for future assessments of IS networks and to understand the contributions IS may have in the biofuel industry. The thesis focuses upon the following research questions and sub-questions.

RQ1- What synergies may be possible between biofuel producers as well as with other industries?

- What exchanges of material and energy are possible between biofuel producers?
- What industrial sectors are possible to build synergies with?
- What types of synergies are most prevalent and what are characteristics of these synergies?

RQ1 will be explored in the text in order to find possible synergies between biofuel producers and external industries. In addition, further details to identify the characteristics of synergies and typical industries to collaborate with will be reviewed and discussed.

RQ2- How can the environmental performance of industrial symbiosis networks be quantified?

- How do previous approaches quantify the environmental performance?
- What can tools such as life cycle assessment provide for quantifications of the environmental performance of IS networks?
- What methodological aspects should be considered when quantifying the IS network?

RQ2 has been included to provide a review of previous attempts to quantify the environmental performance. Thereafter, based on the production of a new approach to quantify IS networks, important methodological aspects and the portrayal of impacts for the total system, as well as for individual firms in the IS network, will be reviewed and discussed.

RQ3- ***How does industrial symbiosis, in the form of material and energy exchanges, influence the environmental performance in the biofuel industry?***

- Under what conditions can IS lead to improvements?
- How sensitive are the results to methodological choices?
- What exchanges are more influential?
- Are the impacts equally distributed between firms involved in the exchanges?

RQ3 addresses the influence that using concepts of IS may have in the biofuel industry. In this thesis, this will relate to an IS network including a biogas, ethanol and combined heat and power (CHP) plant.

The results from this thesis are aimed at providing information for the biofuel industry and researchers to improve environmental performance through the use of IS concepts. This is done to ensure that by-products from the biofuel industry as well as from other industries are used more efficiently for improved resource efficiency and environmental performance. Additionally, the results are aimed at providing the IS research community with insight into quantifications of IS networks and provide an example of an IS network aimed at delivering renewable energy.

1.2 Scope and Limitations of the Research

The research provided in this thesis has been conducted in order to portray the environmental performance of industrial symbiosis in the commercial biofuel industry, which includes ethanol, biogas[5] and to some degree biodiesel production. Much of the research is based on exchanges between ethanol and biogas plants, as data was available regionally for the exchanges from an industrial symbiosis network of biofuel producers. Biodiesel was not included in quantifications as the industrial symbiosis network does not include a biodiesel plant, though possible synergies with biodiesel producers are provided.

Rather than focus on the feasibility of the implementation of IS network or other effects the IS network may have on surrounding systems, the study focuses on the possibilities for improvements in the biofuel industry and how these quantifications are conducted using concepts from industrial symbiosis and life cycle assessment.

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[5] ***Biogas***- refers to the anaerobic digestion process resulting in a raw gas which can be upgraded to biomethane and other gases. Biogas will be used to also refer to the raw gas from the anaerobic digestion process in this thesis.

Assessments do not include rebound effects or other feedback loops of consequential modeling or indirect emissions in the agricultural sector. Furthermore, the approach provided is targeted primarily for the IS community, though the implications of its use for decision making are discussed. The research was carried out from a Swedish perspective, though concepts of integration between the biofuel and external industries may be applicable worldwide, especially for integration between biogas and ethanol plants.

From the results of the thesis, the environmental performance of integration between an ethanol and biogas plant are portrayed. However, the results are not representative of the Händelö IS network and cannot be generalized to other biofuel IS networks, as the conditions may vary. Furthermore, the results are not characteristic of the improvement possibilities of IS in general. Nonetheless, the influence of integration and sensitivity of the environmental performance to methodological considerations and other system aspects can be similar to other cases worldwide.

The research does not compare the uses of the biofuels or provide an assessment of the "best" biofuels, but assumes that all the fuels are needed to support the shift toward a society with more renewable energy. As such, the thesis provides information to produce the biofuels in concert with one another, either through exchanges between the biofuel industries or external industries. The assessments are limited to the improvement of the commercial biofuel industry and biorefinery concepts are not included, though the transition to such a system and similarities with IS systems are discussed. Additionally, increasing demand for biofuels and biomass are not addressed in the thesis, though they are driving forces for biofuel production. The thesis primarily reviews possibilities for existing plants to integrate/collaborate and make use of wastes and by-products for other industries; therefore the use of biomass, a limited resource, is not addressed in particular.

The use of sustainability will refer to environmental sustainability and does not imply other aspects of sustainability, unless otherwise specified.

1.3 Research Journey through the Appended Papers

In order to provide an authentic representation of the development of this thesis, a contextual representation of each paper and the “journey” to the thesis, through the appended papers, is provided.

Paper I

After starting my research at the Division of Environmental Technology and Management, a lot of time was spent reviewing industrial symbiosis and biofuel production literature along with working on LCAs of biofuel production. As the research developed, we decided to write a paper to “position” our research and introduce the IS and biofuel community to the idea of applying IS concepts in the biofuel industry for possibilities to improve the environmental performance. Paper I was therefore produced and functions as a background for all other articles in this thesis. The paper is published in the journal, Biomass and Bioenergy.

Paper II

Together with my co-authors we had the idea to write a research paper which was aimed at classifying the types of exchanges in the industrial symbiosis field based on our research work with partners of the Händelö IS network. Findings from the research resulted in a listing of synergies possible between biofuel industries and with external industries. Further development of this report resulted in a conference paper for the Greening of Industry 2009 Conference in Aalborg, Denmark. The paper outlined possible classification measures to understand more about the exchanges in an industrial symbiosis network. However, the paper did not evolve further than what was included in the licentiate thesis, as the aim of my research after the licentiate was to continue on a more quantitative track; which I was also more interested in. During the Fall of 2009, together with a Master’s thesis student, Jorge Fonseca, I wanted to understand what synergies were possible in the biofuel area and with external industries worldwide. A literature review of scientific articles on possible synergies thus ensued, though we found a large number of articles available. We therefore proceeded to exclude articles using combination words in a systematic approach. The results were combined with the aforementioned paper and included in Paper II. The paper was published in the journal, Biofuels.

Paper III

The quantitative assessments of IS started with the work for Paper III. I began looking into the environmental performance of biogas and ethanol exchanges based on data I collected from the IS network on Händelö. However, as the exchange of by-products between the biogas and ethanol plants was not large, the results did not show a distribution of impacts; the impacts from the system were dominated by the ethanol plant. Therefore, based on the synergies found in Paper II, I began to look at possibilities for "improving" the exchanges between the biogas and ethanol plants to see if the distribution would change if further integration was induced. Scenarios for increased integration between the biogas and ethanol plants were therefore created to understand more about the environmental performance of an integrated system. The research was first used for a report and thereafter revised as conference paper for the World Renewable Energy Congress 2012. The paper was selected for a special issue and revised once more for publication in the journal, Renewable Energy.

Paper IV

Paper III presented results for an integrated system between the ethanol and biogas plants. However, I was interested in understanding how to quantify the environmental performance of an industrial symbiosis network, as the paper reviewed only exchanges between the biogas and ethanol plants. I began setting up scenarios and looking at previous quantification studies produced. It was then concluded that very few quantifications of IS were produced previously, and the methods used were very dissimilar. In order to move forward, I used LCA to guide an approach for quantifications of IS networks while working with Paper V concurrently. The paper was presented at the Greening of Industry 2012 Conference in Linköping and chosen for the special issue in the Journal of Cleaner Production. The manuscript has been revised and resubmitted based on reviewer comments.

Paper V

Using similar data from Paper III in combination with the method from Paper IV, I began quantifying the environmental performance of an integrated biogas, ethanol and CHP plant based on information from Händelö. Many questions about the use of the tool surfaced, especially how to treat the CHP plant and what the main product of the CHP plant was. After reviewing the boiler system with information received from E.ON, I was able to model the system for the biofuel IS network.

Using the method provided in Paper IV, I was able to quantify benefits of the IS network in comparison to reference scenarios and provide the benefits and impacts for each firm of the IS network to provide evidence of how the method could be used. During the production of Paper V, several aspects of the applicability and "user-friendliness" of the method in Paper IV were identified and revised. The manuscript appended to this thesis will be submitted for publication upon acceptance of Paper IV.

2 Biofuel Production and Development

This chapter will provide information about the production of biofuels worldwide. First, a review of the development of the biofuel market is provided, including the promotion and assessment of biofuels. Thereafter, the chapter will also provide a brief overview of biofuel production processes, their raw materials and by-products

In response to the effects of climate change and to reduce our dependency upon fossil fuels, nations have begun promoting biofuel production and development. Policies, in particular, are being used to promote biofuels through blending obligations and targets. As an example, the European Union has introduced the Renewable Energy Directive (EU-RED) that has the aim of 20% greenhouse gas reductions, using 20% less energy and a 20% share of renewable energy by 2020 (European Commission, 2008). Within this policy, the use of biofuels has been promoted to reach these targets. By 2020, a mandatory target of 10% renewable energy should be reached in the transport sector, which will primarily be covered through the use of blended fuels (European Union, 2009b).

With these policies the biofuel industry has seen rapid growth. However, this growth and promotion of biofuels has raised criticism from many aspects related to the sustainability of biofuels. A “trilemma” is thus created to produce sustainable biofuels to address our energy, environmental and food challenges to benefit society (Tilman et al., 2009). A number of studies have been produced in recent years outlining the failure of biofuels to address this “trilemma,” for issues such as land use, energy ratios, emissions and social aspects related to biofuel production practices (Searchinger et al., 2008; Börjesson, 2009; Ponton, 2009; Van Der Voet et al., 2010; Diaz-Chavez, 2011; Timilsina and Shrestha, 2011).

With the increase in criticism of biofuel production, a call for environmental sustainability assessments has led to a drastic increase in the number of life cycle assessments (Cherubini et al., 2009; Cherubini, 2010b; van der Voet et al., 2010). Many studies have therefore been produced to outline whether biofuel production can answer this “trilemma” and offer benefits. National policies have also begun to take into account the sustainability aspects of biofuel production. Policies in the European Union (European Union, 2009b) and United States of America (USA Law, 2007) mandate that environmental sustainability assessments of biofuels be conducted using LCAs of the production process to review the benefits provided compared to fossil alternatives. In addition, the policies also regulate sustainable land use systems to ensure biodiversity. Through these policies, biofuels are supported as substitutes to fossil fuels to ensure that biofuels are produced “right” without the undesirable impacts of biofuels “done wrong,” therefore biofuels must provide positive benefits for several important objectives, including energy efficiency, greenhouse gas emissions, biodiversity and food supply (Tilman et al., 2009).

Using an outlined method for conducting the LCA, the EU-RED (European Union, 2009b) mandates that all biofuels should have greenhouse gas emissions savings of 35% relative to fossil fuels from January 2012. Furthermore, more stringent mandates are set for at least 50% and 60% reductions, from January 2017 and January 2018 respectively (European Union, 2009a). It is uncertain whether many of the current biofuel systems will be able to meet these reductions in future years. Therefore, attention has been focused toward looking into future possibilities of advanced biofuel production[6] through novel technologies (Taylor, 2008; Cherubini, 2010a; Fahd et al., 2012)). Even policies for biofuels promote second generation technologies to ensure the development for the supposed benefits (European Union, 2009b). The current EU-RED (European Union, 2009b) allows for double counting production figures toward member state shares in the transport sector (Bole and Londo, 2010). However, the double counting raises concerns over a dampening effect and the development of the commercial biofuels and whether "indicators" for environmental impacts may be skewed. However, many advanced biofuels remain unproven and immature at the commercial scale with high or uncertain production costs, making estimates of costs, environmental performance and energy efficiency difficult (Wetterlund, 2012). With the lack of advanced biofuels being commercialized, in order to meet the targets for biofuel shares and greenhouse gas savings proposed in the EU-RED, current biofuel systems may need to be improved. Research shows that this can be accomplished through energy efficiency improvements, using new raw materials and making use of by-products from the production processes (Börjesson, 2004b; Murphy and McCarthy, 2005; Murphy and Power, 2008). Systems as such are also available which extend beyond the 60% reductions (Cleantech Östergötland, 2009; Lantmännen Agroetanol AB, 2013).

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[6] The production of biofuels is often divided into many divergent definitions, i.e. first, second and even third generation biofuel production. In this thesis the production of biofuels will be referred to as those commercially available and advanced biofuels. Advanced biofuels will be referred to in this thesis as biofuels which are produced from lignocellulosic feedstocks, including wood, forest residues, grasses and other wastes to produce fuels such as methanol, DME, Fischer-Tropsch diesel, synthetic natural gas and even ethanol through gasification, enzymatic separation and other technologies which are not commercially available.

2.1 Production of Commercial Biofuels

Commercial biofuels have varying production processes using conventional raw materials and industry by-products and are currently available on the market. Commercial biofuels include biogas, ethanol and biodiesel and are produced employing a number of techniques depending upon the fuel; using a variety of raw materials as described in subsequent text.

Biodiesel is produced from fats and oils (e.g. rapeseed and sunflower oil, waste vegetable oil, fish oil, animal fat) through the transesterification process, resulting in a fuel similar to diesel. The transesterification process requires alcohol, catalysts and in some cases acids depending upon the quality of the oil. By-products from the process include glycerol, water, recovered alcohol, seedcake (if seeds are pressed) and even excess heat, though the process rarely runs at a temperature over 60°C (Worldwatch Institute, 2006). Glycerol has been identified as a valuable product which can be used for a number of purposes, ranging from fuel extenders to additives for food production (Donkin et al., 2009; Kiatkittipong et al., 2010; Abad and Turon, 2012).

Ethanol is a product of the fermentation of sugars and starches. Typical ethanol plants in Europe and the USA produce ethanol from starch based biomass (e.g. corn and wheat) and thus saccharification, the breakdown of starch into simple sugars, is needed to commence fermentation. The process requires a great deal of heat, water and enzymes. Besides the production of ethanol, many by-products are also created including carbon dioxide, stillage, thin stillage, heat and other alcohols. In many ethanol production plants the stillage is dried to produce dried distillers grains with solubles (DDGS) which is used as an animal fodder along with thin stillage (Worldwatch Institute, 2006; Murphy and Power, 2008). Oil is also obtained in several ethanol processes, which can be used for e.g. food applications and biodiesel production (Ciftci and Temelli, 2011; Liu et al., 2011a). Carbon dioxide from the ethanol plant is currently released in many systems worldwide, though it may be captured and used for subsequent processing for cooling applications and the beverage industry (Xu et al., 2010).

The biogas production process consists of the anaerobic digestion of organic matter resulting in methane and other gases. This biogas output is referred to in the text hereafter as biomethane[7], while the process refers to biogas. Organic matter and wastes originate from a number of sources; a literal "smörgåsbord" of inputs. These typically include industrial wastes, household wastes and agricultural wastes (Lantz et al., 2007; Linköpings kommun, 2008; Svensk Biogas AB, 2013b). Several by-

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[7] ***Biomethane***- refers to the upgraded gas from a biogas process, containing roughly 98% methane.

products are produced from the biogas process. These include solid and liquid digestate (Lantz et al., 2007; Svensk Biogas AB, 2013b) which have applications as bio-fertilizers or substrates for bioenergy production, i.e. use in CHP plants (Kratzeisen et al., 2010). Besides biomethane, additional gases are produced during the process, e.g. carbon dioxide, hydrogen, hydrogen sulfide and other gases, which may have further applications though they are commonly released to the atmosphere (Lantz et al., 2007; Svensk Biogas AB, 2009).

3 Scientific Background

This chapter will provide the background theories and concepts used in this thesis. The scientific field of industrial ecology, concepts of industrial symbiosis and the life cycle assessment method will be reviewed. To close, the chapter will provide an overview of how these theories and concepts are applied in this thesis in order to position the research.

3.1 Industrial Ecology and Industrial Symbiosis

Using systems thinking enables an entity to be understood best by not seeing it in isolation, but as a part of other systems[8]; i.e. systems are viewed in a holistic manner by using systems analysis. Using systems thinking, or moreover systems analysis, can thus help to explore the dynamic complexity to acquire unique perspectives on all parts of the system. Systems analysis has gained importance as a result of increasing awareness of the interdependence between the environment and our society (Olsson and Sjöstedt, 2004). Often "systems thinking" is referred to as a principle for conducting research in the field of industrial ecology.

Industrial ecology is a research field which attempts to address problems or issues in our world by examining them from a systems perspective by involving aspects of the environment, economy, society and technology. The name "industrial ecology" implies that the field is both *industrial* and *ecological*. The *industrial* reference is due to the fact that it involves product design, manufacturing and sees firms as mediators for environmental improvement. The *ecological* reference denotes its view of natural ecosystems as models for industrial activity, i.e. the biological analogy, in addition to viewing industry in context with ecosystems that support it, to examine resources used and the sinks that act to absorb wastes (Lifset and Graedel, 2002).

The field gained importance after the publishing of an article by Frosch and Gallopoulos (1989) calling for a change in the traditional industrial systems. Central to the research field of industrial ecology is the principal of minimizing wastes through the closing of material and energy loops and viewing ecosystems as examples to be mimicked by industries for the production of sustainable systems (Frosch and Gallopoulos, 1989; Lowe and Evans, 1995; Lowe, 2001). Furthermore, industrial ecology can be described as a broad holistic framework consisting of tools,

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[8] ***Systems*** can be referred to according to Ewertsson and Ingelstam (2005, page 293) as "complex entities composed of material and immaterial as well as human interacting parts and processes, functionally interdependent. In the study of systems, a broad assumption is that the heterogeneous components have to be constructed, dimensioned, arranged and coordinated to interact harmoniously with the others, to function as a well-balanced system."

principles and perspectives, borrowed and adapted from ecology, for the analysis of industrial systems (Lowe and Evans, 1995; Lowenthal and Kastenberg, 1998).

The analysis of industrial systems can be conducted employing tools deriving from the industrial ecology toolbox to analyze flows of materials and energy of industrial activities and the effects they may have on the environment in addition to their influence on economic, political and social factors for resource use, transformation and disposition (White, 1994). These tools encompass a broad range of methods to cover all aspects from a systems perspective. Industrial ecology can be addressed between its systemic-oriented and application oriented elements; systemic analysis and eco-design and other application elements respectively.

Of the systemic oriented elements are the environmental system analysis tools which are used to explore industrial metabolism and life cycle perspectives. Furthermore, studies on social and economic aspects may also be conducted under the systemic analysis studies.

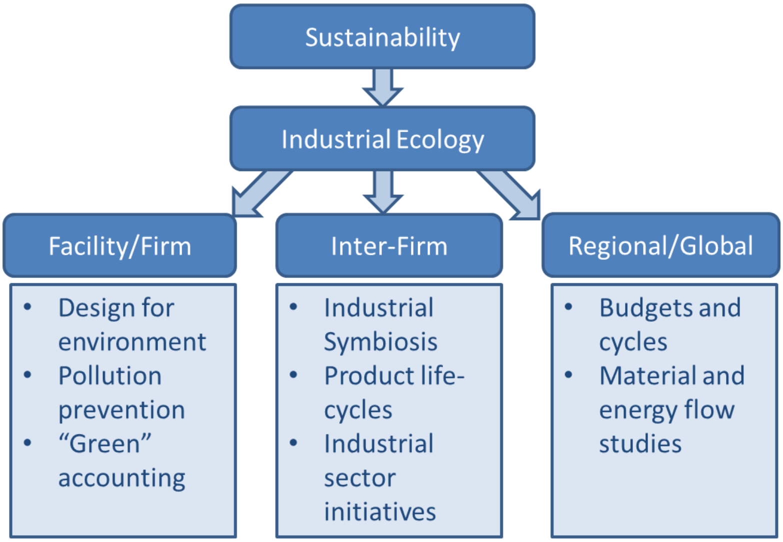

Figure 1: The Three Levels of Industrial Ecology (Chertow, 2000)

Studies of industrial ecology can function and be applied for optimization of industrial activities on several levels, including the global, inter-firm and individual facility level; Figure 1. When information about firms, product life cycles and initiatives to improve industrial sectors are reviewed, the inter-firm level can be reviewed. Within this level is the study of industrial symbiosis.

Industrial symbiosis is research topic of industrial ecology which focuses upon the inter-firm level (Chertow, 2000; Jacobsen, 2006). Through the symbiotic activities between firms, industrial symbiosis provides many relevant contributions to the industrial ecology field by adopting and implementing ecosystem traits to promote sustainable resource use at the inter-firm level. The concepts stem from the symbiotic relationships seen in the natural environment, where organisms exchange energy and materials to mutually benefit. Many of the studies of industrial symbiosis focus on the use and recovery of wastes from one firm as a raw material for another to minimize the input of virgin materials. Using industrial symbiosis, firms may collaborate in a collective approach to create competitive advantages through resource exchanges, where no firm is seen as an island but interacts with other firms to create mutual benefits, promoted through geographical proximity(Chertow, 2000).

The exchanges of resources between firms are fundamental to industrial symbiosis. These exchanges allow firms to handle wastes, raw materials, energy and by-products. By integrating with other systems or building cooperation, *synergies*[9] are created between the industries. The Center of Excellence in Cleaner Production of Curtin University (CECP, 2007) and van Beers et al. (2007) define these exchanges as either by-product or utility synergies. By-product synergies may be defined as synergies which involve the use of previously disposed by-products, residues and wastes which are subsequently used as an input for another firm. These by-products can be used as imminent raw materials, additives or fillers for other firms. Utility synergies involve the sharing of utilities, including the sharing of energy, water, electricity, heat, joint treatment of emissions as well as recovery and treatment plants.

Recently Lombardi and Laybourn (2012) have postulated a new definition of industrial symbiosis to reflect developments from research in the IS community. According to the new definition, many of the "traditional" classifications of what is included in IS can be extended to include new areas important to convey its richness to practitioners and other stakeholders. In the new definition, the geographic proximity requirements are negated and exchanges are extended to include personnel and knowledge transfer. Furthermore, competitive advantages from IS are

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[9] In the text, *synergies* will be used and may be confused with the use of *exchanges* of material and energy. Synergies refer to the cooperation or linking of industrial activities by shared consumption, disposal and reuse of material and utilities. Synergy can therefore be described as a general expression for the exchanges of different types of material and energy; referred to throughout the text as either by-product or utility synergies.

extended beyond resource efficiency to include reduced costs, valorization of products, diversification and management of risks. The authors argue that collaboration for these advantages are initiated by self-interest and not motivated by reduced impacts. Industrial symbiosis has been identified as an approach to improve the sustainability of industrial systems through improvements in material and energy efficiency, assuming that industrial symbiosis will produce win-win situations for all firms involved in the exchanges.

However, it can be identified that the use of IS and IE can be normative. The basis for the concepts of IS included in the evolving field of industrial ecology is that industrial systems should conform to properties of natural ecosystems to be in concert with the surrounding environments and optimize the total material, energy and capital flows. This definition, and the way it is used by researchers, is normative by nature and is accepted by many 'industrial ecologists,' which may then without knowing carry out research subjectively although other methods may also be used outside of the industrial ecology toolbox; further discussion is provided in (Boons and Roome, 2000).

Many studies of industrial symbiosis are concerned primarily with understanding or describing the context for industrial symbiosis (Mirata, 2004; Baas and Boons, 2007; Wolf et al., 2007; Baas and Huisingh, 2008) and in recent years, many studies have been published to "uncover" industrial symbiosis networks worldwide (Chertow, 2007; Van Berkel, 2009). Very few studies concerned with quantifications of the benefits of IS, whether it be economic, environmental or social benefits, have been conducted (Karlsson and Wolf, 2008; Wolf and Karlsson, 2008; van Berkel, 2010; Sokka et al., 2011; Sokka, 2011) despite tools available in the industrial ecology field.

3.2 Environmental Systems Analysis

Systems analysis can be applied in order to explore the environmental aspects and impacts when reviewing the sustainability in studies from the field of industrial ecology using what is known as environmental systems analysis (ESA). According to Wageningen University (2013), ESA can be defined as "the application of systems analysis in the environmental field to describe and analyze the causes, mechanisms, effects of, and potential solution for specific environmental problems." Using systems analysis extends the boundaries to capture the complex nature of the object being studied from a systems perspective.

Within the subject of environmental systems analysis, many tools have been produced to meet demands to grasp many of the challenges of providing for the facilitation of informed decision making, learning purposes and communication of environmental impacts (Moberg, 2006). Environmental systems analysis tools require the use of interdisciplinary approaches to develop new insights to the causes, effects and potential solutions to environmental problems. These tools can be divided into those with a focus on improving decision making and those which provide information for system optimization, communication and comparisons; i.e. procedural and analytical tools respectively (Moberg, 2006); see also Figure 2.

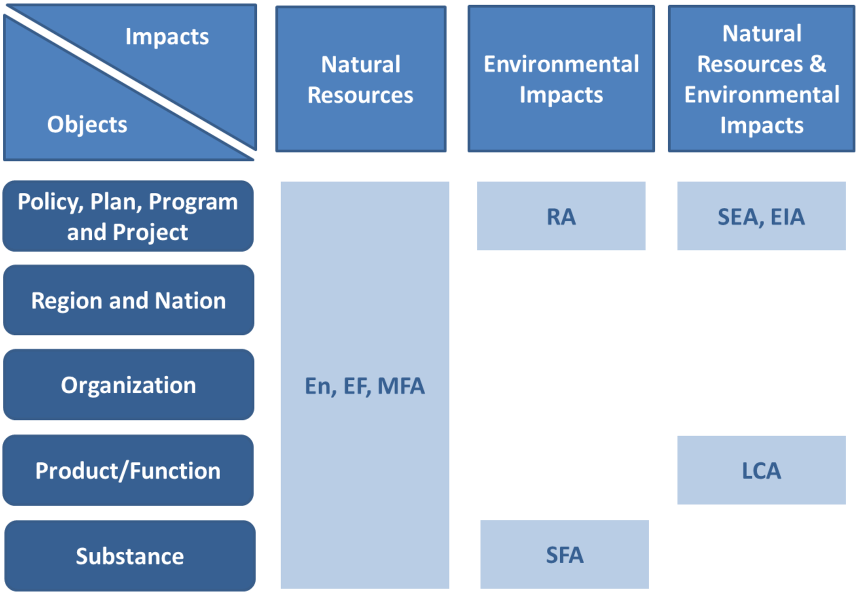

Figure 2: Environmental Systems Analysis Tools and their focus and objects studied. Adapted from Moberg (2010). *En-Energy Analysis, EF-Ecological Footprint, MFA-Material Flow Analysis, RA-Risk Assessment, SFA-Substance Flow Analysis, SEA-Strategic Environmental Assessment, EIA-Environmental Impact Assessment, LCA-Life Cycle Assessment.*

Procedural tools are typically used for the operational management of companies in addition to strategic decision making. These include tools such as strategic environmental assessment (SEA) and environmental impact assessment (EIA) to assess and handle environmental aspects of strategic decision making and environmental impacts of suggested projects and alternatives respectively. Within the analytical tools are a number of tools used to account for material flows and to assess alternatives. Tools such as life cycle assessment (LCA) are used to assess the potential impacts from products and services from a life cycle perspective. Analytical tools may provide technical information used for the procedural tools for strategic decisions.

ESA tools can provide support for decisions on a number of levels depending upon the aspects and context of the decision. Finnveden and Moberg (2005) argue that the object of study and the impacts of interest are used to choose the appropriate tool, while other aspects (e.g. scale of the decision) will influence how the tools are used. Within the inter-firm level of industrial ecology, are industrial symbiosis and product life cycle studies. In order to show the environmental performance of IS networks, which are lacking in the IS literature, tools such as EIA and LCA can be used depending upon whether the analysis is regarded as a project or collection of products respectively. Resource throughput can also be identified using material flow analysis (MFA) studies according to Finnveden (2005). However, as this thesis considers the IS network as a collection of products, rather than a planned project as in the case of eco-industrial parks, LCA methodology will be used to evaluate the environmental performance, i.e. impacts, of the IS network.

3.3 Life Cycle Assessment

Life cycle assessment is based on using a life cycle perspective to estimate the environmental impacts, for all phases of a products lifetime, from cradle-to-grave (ISO, 2006a). The assessments are designed to review all impacts associated with the product and service, from the production of raw materials to the use of products. LCA has been used for several decades and has even been standardized by the International Standards Organization. According to ISO 14044 (2006b), the process is based on four required elements, including 1) goal and scope definition, 2) inventory analysis, 3) environmental impact assessment and 4) interpretation of results, see Figure 3.

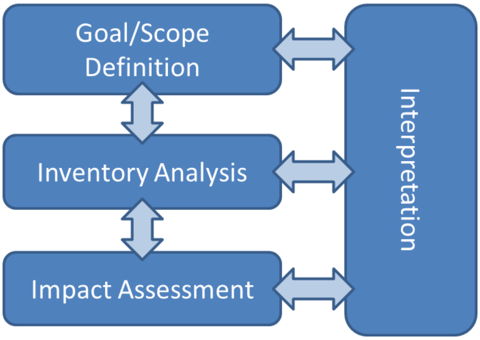

Figure 3: Elements of the Life Cycle Assessment Method (ISO, 2006a)

The goal and scope element of the LCA ensures that the outcome is consistent with the objectives and sets the context for the study. It is therefore important that the purpose of the study is defined. This is done through the definition of the functional unit, the service delivered by the product system, which provides a reference for inputs and outputs to be related. Other important aspects include;

- The definition of system boundaries (what is to be included and what is not), e.g. whether it is a cradle-to-gate study versus a cradle-to-grave study.
- Allocation procedures followed (how impacts are partitioned among products of the system), described in subsequent text.
- Data quality (accuracy of the data and how sensitive it may be to changes).
- Methodology used for the environmental impact assessments.

The inventory analysis is used to collect data necessary for quantifications of environmental impacts of the service or product. This is often done by mapping the applicable material and energy flows. Thereafter, the data is related to the functional unit.

In order to estimate the environmental impacts, the impact assessment element is conducted. In this element, decisions are made as to what environmental impact categories are included. The choice of method for the impact assessment is crucial for the production of the LCA, as the different methods may yield divergent results, depending upon the weighting and characterization factors employed. Therefore, the most appropriate tool for application in the studies is to be chosen. Of the methods available are midpoint and endpoint oriented approaches. Midpoint approaches provide quantitative modeling for equivalent emissions of substances, and end at this point to reduce the uncertainties and biased practices of weighting. Endpoint approaches however, model changes in the environment to show damages.

If the aims of the study are to show the environmental impacts, the midpoint approach is used. The environmental impact categories may include e.g. global warming potential, ozone layer deletion, photochemical oxidation, eutrophication, acidification and the use of non-renewable energy and materials. Thereafter, classifications must be carried out. This includes defining where emissions from the flows of material and energy are allocated between the chosen impact categories. As some emissions will have impacts in several impact categories, characterization factors are included, depending upon the method. The final results provide the basis for interpretation of the LCA (ISO, 2006a).

From the interpretation, the consistency, sensitivity and significant issues can be used to formulate conclusions, recommendations and limitations for the study for communication with external parties. During this process, further iterations may be required in addition to more reliable data as LCA is iterative in nature, requiring revisions to the model and data. Lazarevic (2012, page 3) describes conducting the

LCA as follows, “the goal and scope of the study are defined, a life cycle model is developed, impact assessments produced, the goal and scope are then refined or revised if necessary, key data improved, impact assessment characterization factors are improved, results interpreted, reported and subjected to independent review if necessary.”

3.3.1 Strengths and Limits of LCA

From the analytical tools, LCA is a robust tool which lends itself useful for quantitative assessments of the environmental impacts from products or services. LCA’s strength lies in its comprehensive approach to evaluate upstream and downstream flows of a product or service, avoiding problem shifting between other processes and locations in the life cycle (Hermann et al., 2007; Finnveden et al., 2009)

Finnveden (2000) also states that the use of LCA is warranted by the fact that in order to properly compare products and services, the whole life cycle must be considered as products and services may have different impacts distributed in their life cycles. Furthermore, when trying to show environmental impacts, LCA cannot completely be replaced by any other tool, as other tools do not review the “cradle-to-grave” perspective (ibid).

Although LCA may be a comprehensive tool for quantifying environmental impacts, the process is constantly undergoing development and has its limitations (Finnveden et al., 2009). Conducting an LCA may be considered time consuming and expensive. The assessments are also prone to error. Methodological choices in the LCA such as the choice of functional unit and system boundaries in addition to data reliability issues may be influential for the results (Björklund, 2002; Reap et al., 2008a; Reap et al., 2008b). According to Finnveden (2000), one example is that data for airborne emissions are much more available than emissions to water, thus the extent of the eutrophication emissions are not portrayed. Furthermore, LCAs may not fully model rebound effects and future changes in technology. It is also limited to environmental impacts, and social and economic aspects must be modeled separately and may have limited spatial and temporal resolution (de Haes et al., 2004). Work to broaden LCA with the integration of social and economic aspects is currently being introduced (Jeswani et al., 2010). Despite the information provided by LCAs, conclusions cannot be made on which system is “better,” though they can lead to decisions leading to a better course of action than would have been followed before the LCA (Finnveden, 2000). However, LCAs can increase the environmental knowledge of systems and influential processes in the system leading to large impacts.

3.3.2 Consequential vs. Attributional LCAs

Life cycle assessment can be conducted using several methods for modeling, i.e. attributional and consequential modeling. Finnveden et al. (2009) describe the attributional method as a method to describe environmentally relevant physical flows between the life cycle being studied and its subsystems. Consequential modeling is designed to understand how changes in the system due to decisions will influence the environmental performance.

The methods differ in their use of methodological choices. Attributional LCAs typically use average data while consequential LCAs use marginal[10] data to represent effects of changes in the output of goods on the environmental performance of the system. It can be said that consequential LCAs review the rebound effects that can occur from the changes in the system, e.g. through positive or negative feedbacks regarding the effects of technological improvements and reduced material use which can lead to an increase use in other systems respectively. Allocation in multifunctional processes is also handled differently in the two methods, which are described more thoroughly in the next section. Attributional LCAs use allocation methods to partition environmental impacts to products from the system. This is typically accomplished using physical parameters, e.g. energy, mass or economic values of the products. Consequential LCAs avoid allocation by dividing the process into sub-processes or expanding the system boundaries to include affected parts of other life cycles. Conceptually, consequential modeling is more complex and is highly sensitive to the assumptions used in the modeling (Finnveden et al., 2009).

There have been a number of articles published to outline when attributional and consequential modeling should be used, see e.g. (Tillman, 2000; Ekvall and Weidema, 2004; Ekvall et al., 2005; Brander et al., 2009; Finnveden et al., 2009; Zamagni et al., 2012). Typically, these outline whether the methods can be used for decision making. Nonetheless, Finnveden et al. (2009) find that attributional and consequential methods can be used for decision making in addition for learning purposes, where attributional methods can be applied to find which systems to avoid and consequential methods for the consequences of decisions. However, depending upon the decision being made, the modeling may be different and decision makers may be more concerned with environmental impacts in place of the effects of changes.

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[10] Marginal is referred to as the base that is used from a surplus or deficit of a product. For example, in the production of electricity, marginal electricity refers to the system that is affected by a net change or deficit in production of electricity as a result of a system producing or using electricity.

3.3.3 Partitioning of Environmental Impacts in Multi-functional Processes

When a system produces several products, also referred to as a multi-functional process, the impacts must be partitioned between all the products of the system in the impact assessment element of the LCA. This can be done by using physical properties of the products to partition impacts based on their share of the overall output, e.g. by their weight, energy content or economic gains. Partitioning as such is referred to as physical allocation and is often used in attributional LCAs. Particularly when it comes to the economic value inherent in the products and by-products, the choice may not be straight-forward as the parameters may change and can lead to diverging results for the system (Cherubini, 2010b; van der Voet et al., 2010). It is recommended in the ISO standards that allocation be avoided if possible (ISO, 2006a).

A method referred to as system expansion may also be used. System expansion is designed to avoid allocation by removing impacts from conventional products replaced by by-products of the system (Weidema, 2001). This is done by identifying the equivalent amount of conventional products replaced by a by-product of the system, finding the environmental impacts of producing that product and thereafter removing the impacts from the system. A credit is thus given for by-products from the system. System expansion is a form of consequential modeling, which has been referred to as partial-consequential modeling (Brander et al., 2009) for the avoidance of processes created in the system affecting markets outside the system (Zamagni et al., 2012). Remarkably, it is possible that the results for environmental impacts may be negative when applying the system expansion method. This does not imply that the absolute emissions are negative but that the product and credits provide a reduction elsewhere in the system (Brander et al., 2009).

The issue of allocation in multi-functional processes is a highly controversial topic in the LCA literature (see e.g. (Ekvall and Finnveden, 2001; Wardenaar et al., 2012). According to Guinée et al. (2004) there is no “correct” way to solve this problem in practice or theory; though the solution should be consistent with the research questions addressed and main methodological choices made. Nonetheless, several authors offer possibilities to avoid allocation or methods to conduct the allocation. Weidema (2001) suggests that allocation is nearly always avoidable through the use of system expansion. However, a further understanding of the conventional products replaced by by-products of the system must be undertaken to grasp the processes affected, taking into account many aspects for the change in production (Weidema et al., 1999; Ekvall and Weidema, 2004).

3.3.4 LCAs in Biofuel studies

LCA is the principal tool used to portray the environmental impacts of biofuel systems. Energy analyses are also common to show the efficiency of the processes, showing only the energy inputs and outputs of the system. However, as biofuels are proposed solutions to the climate change and fossil-fuel dependency, they are to be examined in the context from a life cycle perspective in order to ensure that their development does not shift problems to other areas (Bright, 2011). LCAs are conducted in order to assure that biofuel production processes meet greenhouse gas emissions standards, as mentioned in Chapter 2. Van der Voet and Lifset (2011) found that LCA studies have been used for diverse purposes. These include 1) comparing biofuels to fossil alternatives, 2) obtaining information about the main environmental impacts related to biofuels and 3) using LCA to identify main hotspots in the chain. This abundance of studies contributes to data availability and information on new processes, feedstocks and other innovations used for improvements to the biofuel industry. Nonetheless, results from these quantifications have led to diverging outcomes for similar systems. Many of these diverging results can be attributed to the methodological choices used to produce the LCAs (Cherubini et al., 2009; Cherubini, 2010b; van der Voet et al., 2010). According to Cherubini (2010) and van der Voet and Lifset (2010) some of the most influential parameters for life cycle assessment of biofuel systems include:

- Choice or Fossil Reference System
- Allocation methods used for multi-functional processes
- System boundaries
- Functional Unit Choice
- Data inputs
- Treatment of Biogenic Carbon Dioxide Emissions

Quantifications of biofuel production systems have shown a number of sensitive areas which influence the results. Of utmost importance in many studies is the energy system being utilized, which can greatly influence the energy efficiency and environmental impacts (Börjesson, 2009; Börjesson et al., 2010; Eggeman and Verser, 2006). Often biofuel production systems use fossil based energy systems, which display poor energy balances (Börjesson, 2004a).

Furthermore, the treatment of by-products and the methods used to allocate impacts to the by-products can substantially influence the results of the assessments (Börjesson, 2009; Cherubini et al., 2009; Cherubini, 2010b; Cherubini et al., 2011). In the academic literature, allocation is handled primarily with system expansion in addition to energy allocation methods (Wardenaar et al., 2012). However, only a limited number of studies provide the influence of the two methods on the results to assess the importance (van der Voet et al., 2010). Again, in the LCA literature the discussion of allocation is highly controversial (Ekvall and Finnveden, 2001). Nonetheless, policies advocate the use of the energy allocation method; e.g. in the EU-RED (Brander et al., 2009; European Union, 2009b). Energy allocation is considered advantageous due to the fact that relationships between the by-products are constant, while economic allocation may fluctuate (Börjesson, 2009).

3.4 Previous Quantifications of the Environmental Performance of Industrial Symbiosis

Past attempts to quantify industrial symbiosis, although limited in number, have included a variety of methodological choices. While some studies review the entire IS network, others review only a select few exchanges in the IS network, with the inclusion of upstream and downstream impacts of the industrial symbiosis also varying (Wolf and Karlsson, 2008; Mattila et al., 2010; Sokka et al., 2011). These studies, from a life cycle perspective, review only the production phase and fail to include the emissions from raw material extraction to final handling of the product or processes by not reviewing the entire life cycle from cradle-to-grave. According to Sokka (2011), many of the studies quantifying environmental impacts of industrial symbiosis networks have concentrated primarily on the direct impacts of the symbiosis and do not involve upstream and downstream impacts. Allocation methods also vary in the assessments, with some studies using recommendations from LCA literature while others provide no transparent review of the methods used.

No standardized guidelines are available for how to quantify the environmental performance or benefits provided from an industrial symbiosis networks (Mattila et al., 2010; van Berkel, 2010; Mattila et al., 2012). Furthermore, life cycle assessment, a tool from the industrial ecology toolbox for quantifying the environmental impacts of processes, is seldom applied (Wolf and Karlsson, 2008), though it has been identified as a suitable tool for quantifying IS (Chertow and Lombardi, 2005; Singh et al., 2007; Eckelman and Chertow, 2009; Sokka et al., 2011; Mattila et al., 2012).

First of all, what is being compared or quantified, i.e. in LCA terminology the functional unit, has varied between studies. Several of the available studies focus primarily on the impacts of a selected few exchanges (Chertow and Lombardi, 2005; Jacobsen, 2006; van Berkel et al., 2009). Other studies review the impacts of an entire IS network (Sokka et al., 2008; Wolf and Karlsson, 2008; Mattila et al., 2010; Sokka et al., 2011), making the comparison of such studies difficult. Furthermore, when studies define the functional unit as the total output of the system, methodological issues related to the comparison of a reference system may be difficult. This is due to the fact that the outputs of a reference system and the existing or proposed system may vary. Sokka et al. (2011) and Matilla et al. (2010) have taken care of this by using system expansion to deduct impacts from the reference system due to excess production when comparing the total output of the IS network and reference scenarios. Nonetheless, the comparison of impacts of the total system may fail to present employable data for actors or firms in the IS network.

Typically in IS quantification studies, a reference system is chosen and compared to the current or proposed IS network in order to compare the environmental performance or other indicators. The reference systems are modeled to receive material and energy from outside the IS network to replace by-product or utility exchanges. However, since this system is only speculative, choices made for the non-symbiotic activity may be difficult and there is considerable uncertainty as replacement flows and substituted products may have been avoided by improvements or reductions to by-product streams or even eliminating them (van Berkel, 2010). Previous quantifications have used a variety of reference systems (Chertow and Lombardi, 2005; Sokka et al., 2011; Mattila et al., 2012). Sokka (2011) provides an array of reference systems for various assumptions of replaced flows of material and energy for a system with no material and energy exchanges to compare with an IS network in the forest industry. By doing so, the choice of several reference systems may be used to review the sensitivity to the choice of reference system. This is also done by Wolf and Karlsson (2008) where a fossil energy system is chosen for the comparisons.

Often, resource savings are shown for individual firms involved in the exchanges (Chertow and Lombardi, 2005; Jacobsen, 2006; van Berkel et al., 2009), though environmental impacts for individual firms are rarely portrayed and may be underestimated by only showing resource savings. When LCA has been applied, the allocation methods used in the previous studies have also varied. Many studies look at the total IS network and thus no allocation methods are used, unless to remove excess products as aforementioned in the work of Sokka et al. (2011). Mattila et al. (2012) provide recommendations for the type of analysis to produce, i.e. using attributional or consequential modeling, based on the decision support from the assessment and availability of the data.

3.5 Point of Departure

The preceding sections have outlined several of the important theoretical contributions and concepts used as the background to this study. Nonetheless, I would like to further illustrate my position and use of these concepts and theories. This will be done by first describing how industrial symbiosis concepts are used in this thesis. Thereafter, an explanation of the handling of consequential versus attributional LCAs will be reviewed.

While the study focuses upon the biofuel industry, it is not a *characteristic* biofuel study. The thesis analyzes how the biofuel industry could improve its environmental performance through the exchange of material and energy between biofuel plants and external industries. Concepts from industrial symbiosis are therefore used as a background to describe these material and energy exchanges and the possibilities for environmental performance improvements. Thereafter, the environmental performance will be quantified through the use of methods from life cycle assessment. The thesis can thus bring together IS and LCA to provide an approach for the quantifications. Results from the thesis are intended to be used by the IS and biofuel communities and does not provide a major contribution to the LCA literature.

3.5.1 Industrial Symbiosis Concept and Taxonomy

The research provided in this thesis uses many concepts from the industrial symbiosis literature to outline potential improvements in the biofuel industry. The focus is therefore primarily upon the *traditional* view of IS, concerned with the exchange of material and energy and not the new definition of IS presented by Lombardi and Laybourn (2012), which has more focus upon innovation.

Although the later definition of IS aims to describe the developments in the research of IS and what it encompasses, classifying terms in the research of industrial symbiosis has been difficult due to the fact that the terms used to describe IS concepts have varied meanings between disciplines and authors (Van Berkel, 2009), despite a taxonomy provided by Chertow (2000). Furthermore, definitions have changed as research progresses in the IS research community (Lombardi and Laybourn, 2012). Despite the variety of terms used to describe aspects of IS research, the following taxonomy will be used in this thesis to portray industrial symbiosis concepts and terms (Martin, 2010):

- ***Industrial Ecology***- a broad holistic framework consisting of tools, principles and perspectives borrowed and adapted from ecology for the analysis of industrial systems including the impacts on society and the environment of the systems' material, energy and information flows. (Lowe & Evans, 1995; Lowenthal & Kastenberg, 1998)

- ***Industrial Symbiosis***- an area of research focused on collective resource optimization based on by-product exchanges and utility sharing that mimics natural eco-systems (Jacobsen, 2006).
- ***Industrial symbiosis network***- a network of firms involved in the exchange of material and energy.
- ***Synergies***- the cooperation between industrial activities by the shared consumption, disposal and reuse of material and utilities, i.e. material and energy exchanges. Synergies are the individual linkages between the companies within an industrial symbiosis network.
- ***By-product synergies***- the exchanges of material by-products and wastes between firms in a symbiotic network (CECP, 2007).
- ***Utility Synergies***- the exchanges of utilities (power, steam, compressed air, etc.) and sharing of utility infrastructure (CECP, 2007).
- ***Firm***- separate commercial enterprises or facilities either within the industrial symbiosis network or outside.

3.5.2 Applying Consequential and Attributional Methods

Often in academic studies, there is a dispute about the use of consequential assessments, what it is, how much it covers, what should be included. In this thesis and appended papers, the life cycle assessments have been conducted using both attributional and consequential methods to show the sensitivity to the choice of method, through the use of energy allocation and system expansion respectively.

Attributional methods are applied to partition impacts using e.g. energy allocation. Again, this is due to the fact that energy allocations are used in many biofuel LCA studies in addition to policies. The system expansion method is also used in the thesis and appended papers. As mentioned previously, the system expansion method is common in biofuel LCA studies and is usually compared with the energy allocation method to show the influence of the methods on the results (van der Voet et al., 2010; Wardenaar et al., 2012). The system expansion method is a form of consequential modeling, as previously stated. However, the use of system expansion does not cover the full extent of consequential modeling, given the defined system boundaries of the appended papers. Furthermore, the use of the system expansion is typically conducted similar to an attributional model, i.e. using average data, and processes avoided by by-products of the system deducted; further system changes are not typically modeled. Currently, there are not many consequential studies applied in the biofuel industry, though hybrid methods are available (van der Voet et al., 2010). Nonetheless, as this thesis contains a collection of industries and products this would lead to a largely complex model of the system. In the biofuel industry, issues related to consequential modeling, e.g. indirect land use changes, are currently being resolved in the LCA literature (van der Voet et al., 2010), and are beyond the scope of this thesis. Therefore, the modeling used in this thesis can be described as a partial consequential method (Brander et al., 2009) which only covers the substitution of by-products produced from the system; downstream impacts and other effects (e.g. rebound effects) will not be covered.

4 Methodology

In this chapter I will elaborate upon and motivate the choice of methods employed in the research for this thesis.

The appended papers of this thesis have employed a variety of methods and approaches. Most of the papers have employed literature reviews to obtain information from the relevant research fields and interviews in order to gather data. Quantitative assessments were carried out using life cycle assessment guidelines, while Paper IV provides a method for quantification based on LCA. Table 1 offers an overview of the research questions addressed in the appended papers and the methods and approaches used.

Table 1: Research Questions and their relation to the methods and approaches used in the appended papers

Paper	**Research Question Addressed**	**Method/Approach**	**Contribution**	**Notes**
I	*RQ1*	• Literature Review	Review of how IS can be used in the biofuel industry	Addressed in Chapter 4.1
II	*RQ1*	• Literature Review • Focus Group Interview	Provides possible synergies between biofuel and external industries	Addressed in Chapter 4.1
III	*RQ3*	• LCA • Scenario Analysis	Provides a quantification of scenarios for increased integration between biogas and ethanol producers	Addressed in Chapter 4.3 and Chapter 5
IV	*RQ2*	• Literature Review • LCA • New Approach	Reviews previous approaches to quantify IS and provides a new approach based on LCA	Addressed in Chapter 4.2 and Chapter 7
V	*RQ3*	• LCA and New Approach	Quantifies an IS Network in the biofuel industry using the approach of Paper IV	Addressed in Chapter 4.3

4.1 Interviews and Literature Reviews

Interviews and literature reviews have been conducted in this thesis for several of the appended papers to answer the research questions. While the majority of the literature reviews were used to find papers outlining specific topics related to the theories and concepts and their application, detailed literature reviews were also conducted. The following sections outline the focus group interview and systematic literature review used for Paper II to answer *RQ1*.

4.1.1 Focus Group

A focus group interview was conducted with a reference group of biofuel producers from the region of Östergötland to identify synergies between biofuel producers in addition to possibilities with external industries. The workshops were also produced for all participants to learn from each other and create a forum for the participants to meet, discuss possibilities and share knowledge. Participants were selected from Svensk Biogas AB (process engineer), Ageratec AB (sales support manager and laboratory manager) and Lantmännen Agroetanol AB (plant manager and process engineer) and 4 academic participants from the Division of Environmental Technology and Management of Linköping University, including 2 assistant professors, a professor and the author.

The focus group interview, referred to as a synergy development workshop in Paper II, was conducted due to its strength as an interviewing technique for creative interaction between individuals in a group. Additionally, focus group interviews are widely used as they are a cost effective technique for interviewing several people at once, and allow for the facilitation of ideas and experiences that might be underdeveloped in typical interviews. Participants are also allowed to reflect upon each other's ideas (Kitzinger, 1994). Williams and Katz (2001) define the focus group as a group assembled by a moderator who uses the group and its interactions to gather information about a particular issue (Williams and Katz, 2001).

Synergy development workshops, as outlined by the CECP (2007), use a similar technique for identifying possible synergies between firms. The method according to the CECP (CECP, 2007) allows for the creative input from industry representatives to identify and screen potential synergies based on process inputs and outputs from experts in the field.

Focus groups also have weaknesses attributed to the nature of the group discussions and the facilitators. Sensitive information may not be discussed among groups and participants may tend to conform to popular opinion, thus polarizing the results. Furthermore, some issues may result in arguments. However, the facilitator can eliminate many of these weaknesses by planning and steering the group away from any issues (NOAA, 2009). The selection of participants can also influence the results.

The focus group interview used in Paper II followed a semi-structured method encouraging interaction between the participants. The participants were selected to provide information from both management and process engineering perspectives as the CECP (2007) recommends that experts be used for such assessments. During the interview, the facilitator asked questions relating to synergies possible between the firms and with outside industries guided by the facilitator. Participants were thereafter encouraged to identify possible synergies which they noted on post-it notes, at first individually to provide each participant an individual voice, which were then discussed, arranged and sorted thematically. Furthermore, the interview was recorded and later transcribed. The participants were then provided the results for review and revision. Additional details are described in Paper II.

4.1.2 Systematic Literature Review

A literature review was also conducted to find possible synergies between biofuel and external industries in the academic literature. The systematic literature review method was used as it allows for exclusion criteria to find relevant articles (Green et al., 2006); in this case, finding articles concerned with biofuel synergies.

The method allowed for the sorting of more than 24,000 articles to include 113 unique synergies consisting of a step-by-step process in order to exclude non-relevant literature from the bountiful literature dealing with biofuels. The first step was to review articles related to biogas, ethanol, biodiesel and biofuels in general between the years 2000-2012. Thereafter, using combination words, the articles were concentrated to only include articles containing those keywords along with the aforementioned biofuels and a final review ensued. Nonetheless, before the final review, the exclusion of articles may have removed many potential synergies due to the initial exclusions and as such cannot find *all* relevant articles. However, due to the magnitude of articles found, it was concluded that many unique potential synergies existed in the literature, which were identified for Paper II.

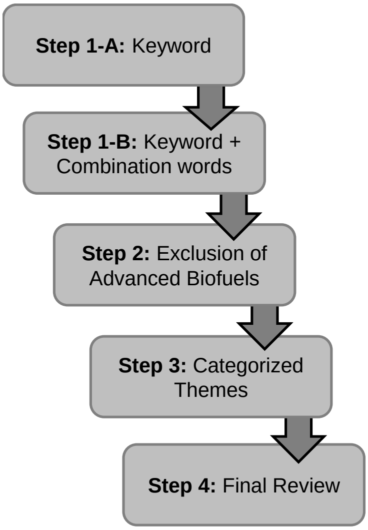

Figure 4: Literature Review Process (Paper II)

The results were combined with the synergies found from the focus group interview. More information on the literature review method and focus group interview is provided in Paper II. From the combination of the two methods it was possible to realize academic as well as practitioner perspectives on synergies within and outside the biofuel industry through triangulation of data sources (Eisenhardt and Graebner, 1989; Stake, 1995).

4.2 Development of an Approach

In Chapter 3.4, an account of the available literature for quantifying IS was outlined. A literature review was conducted to find studies of past IS quantifications, using different methods, e.g. life cycle assessment, material flow analysis, etc. From the review of these methods, it was found that the majority contained a life cycle perspective, or mentioned life cycle assessment as a relevant tool for the quantifications; see e.g. (Chertow and Lombardi, 2005; Singh et al., 2007; Eckelman and Chertow, 2009; Sokka et al., 2011; Mattila et al., 2012).

As mentioned in Chapter 3.2, many environmental systems analysis tools are available to quantify environmental impacts and resource consumption. However, of the tools, life cycle assessment was identified as the most appropriate tool for quantifying products and services of industrial symbiosis networks in the biofuel industry as the thesis considers the IS network as a collection of products rather than a planned project. Furthermore, LCA is the principal tool used in environmental performance quantifications of biofuel systems in both academic literature and policies, and as aforementioned, found in previous quantifications as an appropriate tool.

Thereafter, using life cycle assessment literature and guidelines as references for quantifying the environmental performance (see e.g. (ISO, 2006a; ISO, 2006b)), the available quantifications were analyzed based on their methodological choices for the assessment. From the literature review, it was apparent that further guidelines were needed in the IS field for quantifications as methodological choices varied considerably between the different studies and were not transparent (Martin et al., 2012).

An approach to quantifying IS was therefore produced in Paper IV, which gives recommendations for the methodological choices when conducting environmental performance quantification of IS studies including many of the primary choices from LCA literature, e.g. the choice of functional unit, system boundaries and allocation methods. The approach also outlines how comparisons can be conducted to show whether the IS network is advantageous to a reference scenario by reviewing and providing guidance for the choice of reference scenario to compare with. The results also outline a method to distribute impacts and benefits created through the exchanges to firms of the IS network. More information on the approach can be found in Chapter 7 and Paper IV.

While the approach offers the methodological guidance for conducting environmental performance quantifications of industrial symbiosis networks, it also has weaknesses. As with life cycle assessments, the results are influenced by the methodological choices made for the assessments and some of the recommendations may be disputed. One such choice is to avoid consequential modeling and only apply physical allocation and system expansion, which limits the applicability to answer some research questions related to IS networks. However, for the research questions which the approach aims to address, and according to the recommendations of Mattila et al. (2012), it was concluded that choice of physical allocation and system expansion were warranted. Furthermore, the two chosen methods are recommended for the quantifications, in order to show the influence they have on the results.

It should be noted again that the approach is not intended to be a new addition to the LCA literature, but offer possibilities for quantifications of IS networks in the IS research community to link the two research areas together, although the approach provides a novel method for distributing impacts for integrated systems. The approach uses LCA methods and guidelines to outline how the IS network quantifications could be produced. As such, many of the recommendations provided in the approach of Paper IV also have limitations from both research areas. Further discussions on the limitations of the approach are provided in Chapter 7, Paper IV and the discussion chapter of this thesis.

4.3 Quantifying the Environmental Performance of an IS Network

The following section presents the methods used to conduct the environmental performance quantifications of an IS network based on Händelö used to answer *RQ3*. First, motivation for the use of Händelö and how it is used as a case is provided. Thereafter, the data collection methods are reviewed, followed by a description of the tools and methodological choices for life cycle assessments.

4.3.1 The IS Network of Händelö

The analyses of several of the appended papers were based on data from the industrial symbiosis network on the island of Händelö, Norrköping due to the unique nature of the exchanges between firms. Händelö, unlike many industrial symbiosis networks, is a collection of renewable energy producers collaborating in what has been termed the "bioenergy complex," where the concepts of industrial symbiosis are exemplified in a non-fossil system, see Figure 5. Furthermore, as the IS network was located regionally, the accessibility and potential for data gathering from field visits, interviews, etc. was greatly alleviated.

Händelö has been used in this thesis and appended papers as a *case* for the assessment, and not as a *case study* (Yin, 1994). However, some of the concepts from case study research are relevant for application in quantitative assessments as provided in this thesis, including the use of triangulation of data sources and using the results to challenge theories, although it does not follow methods provided by case study research (Yin, 1994; Stake, 1995).

As the assessments were primarily quantitative, data collected for the assessments of the scenarios were obtained from a number of sources. Interviews, questionnaires (in the form of input-output sheets) and study visits were used as different sources for data. Interviews were mainly conducted in concert with study visits to the plants with industry representatives to collectively produce input-output data sheets for the quantitative studies in Papers III and V, in order to review the results from the questionnaires and clear up any data concerns or questions. Data was also obtained using literature reviews, which were conducted for all papers when data was not available; further information on data for the assessments are provided in subsequent sections. The result was a compilation, or triangulation, of data sources which is described by Stake (1995) as a means to provide more convincing and accurate data and assure validity and credibility. However, the data was received from the individual plants at different periods of time and does not provide an accurate representation of the existing network of Händelö. As such, scenarios are produced based on the data; described further in Chapter 4.3.4 and Chapter 5. The use of data from the IS network on Händelö was used to challenge theories and represent a unique situation, as well as to strengthen theories (Yin, 1994; Stake, 1995) to provide results for the biofuel and industrial symbiosis communities.

As the IS network of Händelö was chosen for the assessments in this thesis, the quantifications are conducted using Swedish conditions. Similar IS networks worldwide may have diverse conditions, energy systems and even possibilities for co-location. These dissimilar conditions should be considered when reviewing this thesis, as the results cannot be generalized for similar IS networks.

4.3.2 Other data used in the assessments

Data from processes and products outside Händelö have been obtained to model regional conditions as well as possible. The cultivation of grains and production of fertilizers have been obtained from earlier research of ethanol production in Sweden (Bernesson et al., 2006; Börjesson et al., 2010). Electricity is assumed to be average Swedish electricity production, based primarily upon hydro and nuclear power (Bernesson et al., 2006). Process heat is assumed to be provided by combined heat and power plants fueled by biomass, as described for the E.ON plant on Händelö in Chapter 5 (E.ON Värme Sverige, 2009; Lantmännen Agroetanol AB, 2013) with data for emissions from (Börjesson et al., 2010). In the absence of data, comparable processes and data have been obtained from the Ecoinvent database v. 2.2, including e.g. transportation processes (Ecoinvent, 2007). Further details on the data employed are provided in the appended papers.

4.3.3 Using Life Cycle Assessment for IS Quantifications

The quantitative assessments are carried out using a life cycle approach with a cradle-to-gate perspective. This includes the upstream impacts of raw materials and fuels; the final use of products is not considered. For the system expansion method, avoided impacts from avoided conventional products replaced by by-products of the system are included in the assessment.

The software package SimaPro v. 7.3.1 was used to conduct the life cycle assessments (Pré Consultants, 2010). SimaPro is a common tool used for general LCAs of products and can be used for the entire product life cycle in a comprehensive and transparent manner(Simon et al., 2012) and includes several exhaustive databases, e.g. Ecoinvent (Ecoinvent, 2007). Jönbrink et al. (2000) also report that the software is suitable for cradle-to-gate studies. Furthermore, SimaPro complies with several ISO standards, including ISO 14025, 14041 and 14048 (Jönbrink et al., 2000; Pré Consultants, 2010) for conducting and reporting the life cycle assessment. Finally, it has also been found in several studies that among similar tools, SimaPro is one of the most widely adopted (Siegenthaler et al., 2005; Cooper and Fava, 2006; Simon et al., 2012).

For characterization factors, the Environmental Product Declaration 2008 (EPD2008) method was used for midpoint analysis as it is recommended by the Swedish Environmental Management Council and provides a relevant selection of environmental impact categories to cover local and global impacts for products and services (Environdec, 2009). These include global warming potential (GWP) for 100 years, eutrophication, acidification, non-renewable resource use and ozone layer depletion. Midpoint analysis was chosen as it provides quantitative modeling for the emissions, and thus reduces uncertainties and biased practices of weighting in endpoint approaches. However, the EPD2008 method chosen does not account for biogenic carbon dioxide emissions[11] emitted from the system and likewise carbon dioxide used for photosynthesis is not accounted for; which is a questionable approach; see e.g. (Rabl et al., 2007; Searchinger et al., 2009; Johnson, 2012). By neither modeling carbon uptake nor the release of carbon to the atmosphere, as this study ends at the “gate” of the analysis, it has been identified that no issues with the carbon accounting would be induced.

In the appended papers, not all impact categories from the EPD2008 method are depicted. In Paper III, only GWP, acidification and eutrophication have been portrayed in the results based on their relatively large impacts to the system. As many biofuels studies and polices take into account only the greenhouse gas emissions, in Paper V only the GWP impacts of the systems are compared. This was done in order to show the robustness of the method from Paper IV and to simplify the quantifications.

As outlined in Chapter 3.3 the LCA method is undergoing constant development and thus has a number of weaknesses. These include for example applying consequential versus attributional methods, partitioning of impacts in multifunctional processes, data used for the assessment and the choice of system boundaries and functional units, see e.g. (Finnveden, 2000; Ekvall and Finnveden, 2001; Finnveden et al., 2009; Wardenaar et al., 2012). Each of these methodological choices may have large influence on the results; see Chapter 3.3 which reviews more these weaknesses in more detail. The methodological choices made and their possible influence on the results will be discussed more in detail in subsequent sections of this thesis.

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[11] Biogenic carbon refers to carbon dioxide released from e.g. the combustion or fermentation of biomass. Since the carbon dioxide was obtained from carbon dioxide in the air through photosynthesis, it is “stored” in the biomass and released as biogenic carbon.

4.3.4 Scenario Analysis

Scenarios have been used in the assessments of this thesis based on the data from the Händelö IS network. Analysis with scenarios is proposed as a method to answer questions such as "what will, what can and how" to understand impacts in the future (Börjeson et al., 2006). The questions addressed offer approaches for explorative studies to see how changes in the system will affect the environmental impacts. In environmental systems analysis tools, scenarios are often used to understand or describe the impacts for future systems especially in LCAs (Höjer et al., 2008). However, the use of scenario analysis may have weaknesses, beyond those present for LCA. Scenario analysis usually requires extensive data, which may only be available for current or past systems and modeling trends may prove difficult. Furthermore, modeling future scenarios and the consequences may be resource demanding for the practitioners. Nonetheless, scenarios can be constructed, as recommended in the literature, to answer the research questions being addressed in the study (ibid). This thesis therefore uses scenario analysis to address the influence of integration or exchanges between biofuel and external industries on the environmental performance; with primary focus on the exchanges between ethanol and biogas plants.

In Paper III, scenarios were designed based on the results of Paper II which could be applied between the ethanol and biogas plants. According to Börjeson et al. (2006) techniques such as the use of focus groups, as used in Paper II, are applicable for *generating techniques* used in scenario analysis. The scenarios were designed to incorporate increased integration between the plants from the existing system to a system with many exchanges. These included using all stillage for biogas production, using biogas for process energy and flue gas treatment and pipelines instead of trucks for the shipment of stillage. Other synergies were also mentioned, but not modeled in the scenarios in the appended papers, e.g. using drying equipment for the collective drying of stillage and digestate from the biogas plant. In this thesis, reference scenarios of speculative cases where no exchanges have taken place are also included and compared not as a historic representation of the system, but what could have been the case if no exchanges had taken place. Paper V however, reviews only a reference scenario and compares it to an industrial symbiosis network based on Händelö, but also reviews how the choice of the reference scenario may influence the results.

5 Händelö IS Network and Scenarios used in Papers

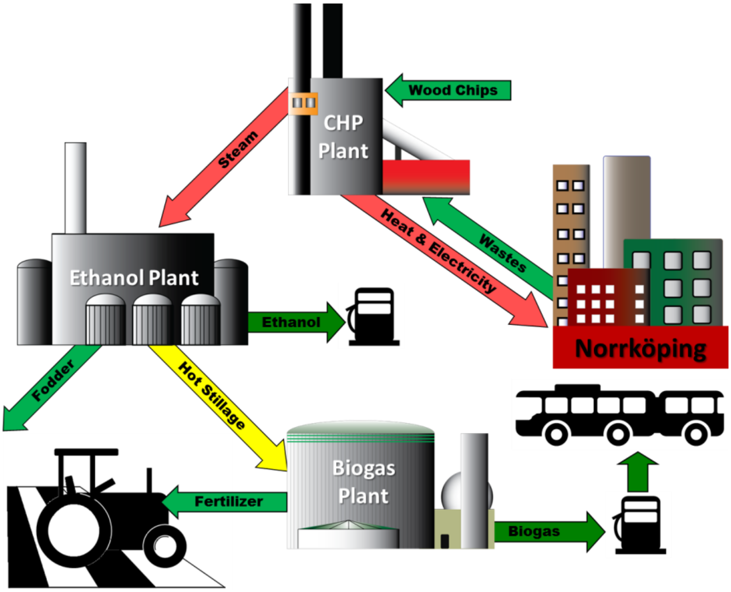

Figure 5: An overview of exchanges in the Händelö IS Network (Modified from Paper I)

Just outside the city of Norrköping, Sweden is the island of Händelö. On the island is an IS network formed by a unique energy and biofuel production plants. These include the ethanol plant of Lantmännen Agroetanol AB, the biogas plant of Svensk Biogas AB and the combined heat and power (CHP) plant of E.ON which produce renewable biofuels, district heating and electricity for industries on the island and the residents of Norrköping (E.ON Värme Sverige, 2009).

Figure 5 provides an illustration of the exchanges between the biogas, ethanol and CHP plants of the IS network on Händelö, which include:

- the exchange of stillage and filtered grains from the ethanol plant to the biogas plant,
- Heat, in the form of steam, delivered to the ethanol plant from the CHP plant
- Heat delivered back to the CHP plant from the ethanol plant

The ethanol plant produces ethanol, used for low blending with petrol in Sweden, in addition to dried distillers grains with solubles (DDGS) which is used as an animal fodder (Lantmännen Agroetanol AB, 2013). Excess heat from the ethanol plant is also sent back to the CHP plant and used for district heating (E.ON Värme Sverige, 2009; E.ON, 2012). Biomethane from the biogas plant is used in buses for the local public transportation system. Additionally the biogas plant produces digestate which is used as a biofertilizer regionally (Lantmännen Agroetanol AB, 2013; Svensk Biogas AB, 2013b).

The fuel for the CHP plant consists primarily of forest industry wastes and household wastes (E.ON Värme Sverige, 2009; E.ON, 2012). However, as the CHP plant contains a number of different boilers, and produces heat for several industries and the district heating system, in this thesis and appended papers it has been assumed that the boiler runs independently of the other boilers fueled entirely by forest industry wastes.

While producing this thesis several changes to the Händelö system have happened or are planned to happen. The biogas plant will no longer receive lower share of stillage from the ethanol plant and instead a large share of the substrate will be obtained from household wastes in Norrköping (Svensk Biogas AB, 2013a) due to the economy of the exchanges. Furthermore, the ethanol plant has also signed a contract with AGA gas to capture the carbon dioxide from the ethanol production process for further uses (Lantmännen Agroetanol AB, 2013). During the production of this thesis, several possible attempts to include a biodiesel production plant were also discussed. The biodiesel plant would possibly have used ethanol for the transesterification reaction and provide glycerol to the biogas plant, further linking the industries (Nicklasson, 2007). Nonetheless, this connection has been delayed and dismissed several times, due largely to economic reasons (Ageratec AB, 2009; Alfa Laval, 2012).

5.1 Scenarios Employed in Papers

5.1.1 Increasing Integration between Ethanol and Biogas Plants

Paper III reviews the possibility for integration of ethanol and biogas production, using varying degrees of integration. The analysis reviews a reference scenario[12], referred to as a stand-alone scenario, and thereafter scenarios for increased exchange of materials and energy between the ethanol and biogas plants. Since the outputs of the system vary, such as the output of biogas, the functional unit for each has been set the same, i.e. 1,314 TJ of ethanol per year, as the ethanol has been considered the main product of the system and to allow for comparisons.

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[12] In Paper III the Reference Scenario has been referred to as a Stand-Alone Scenario. In Papers IV and V however these are referred to as Reference Scenarios.

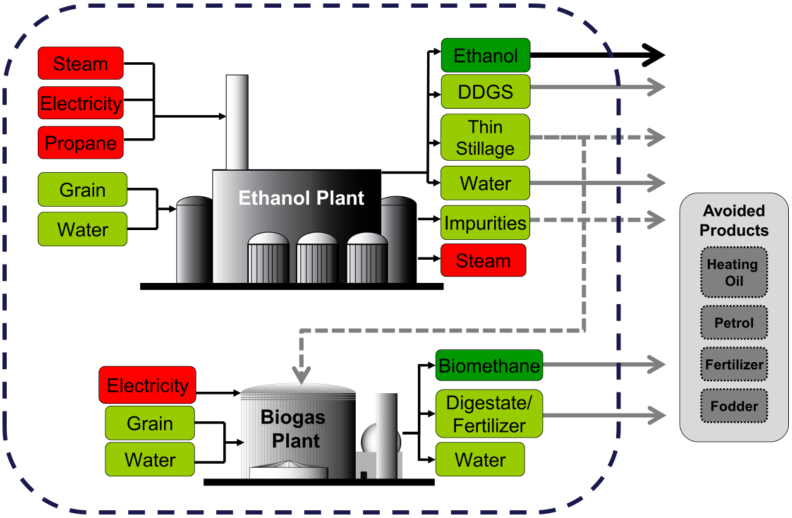

Figure 6: Inputs and outputs for the Stand-Alone and Existing Scenarios as well as Scenario 1. Dashed lines represent possible exchanges for each respective scenario (Updated from Paper III).

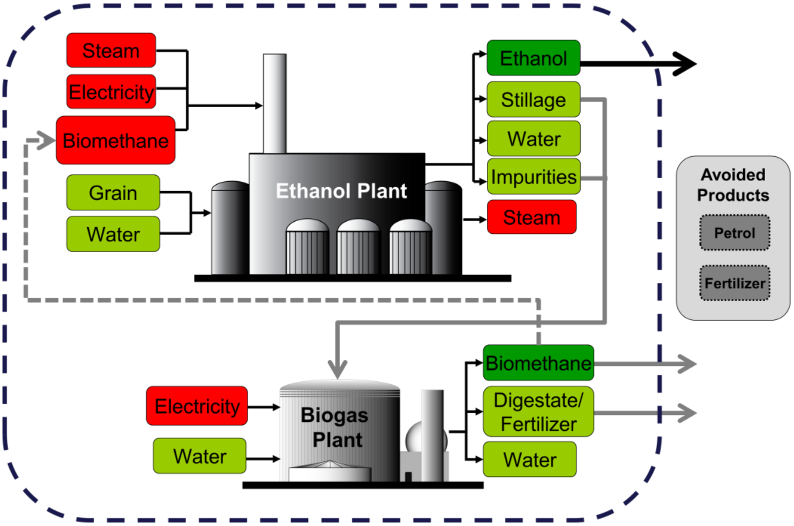

Figure 7: Inputs and outputs of Scenarios 2, 3 and 4. Note that the biogas is used in place of propane in Scenarios 3 and 4, denoted with a dashed arrow (Updated from Paper III).

The basis for the study is the existing scenario, which is built on pre-2009 data from firms of the Händelö IS network with an exchange of thin stillage between the ethanol and biogas plants, depicted with a dashed arrow between the plants in Figure 6. Major by-products of the system include 17 TJ of upgraded biomethane, impurities, DDGS and digestate. Avoided products due to the aforementioned by-products include petrol, oil, fodder and fertilizers.

In order to compare to a system with no exchanges, a reference scenario has been included. Again, the output includes 1,314 TJ of ethanol and by-products including 17 TJ of biogas, DDGS, digestate and impurities. In the Stand-Alone Scenario, no exchanges take place; see Figure 6.

To test further integration, in Scenario 1 the impurities produced in the existing scenario are used in the biogas plant for increased biogas production, which is denoted with a dashed line in Figure 6. The outputs once again include 1,314 TJ of ethanol and DDGS from the ethanol plant. The biogas plant produces 30 TJ of biomethane in addition to digestate. Avoided products of the system include petrol, fertilizer and fodder.

Scenario 2 tests an integrated system where all the stillage and impurities from the ethanol plant are used for anaerobic digestion; see Figure 7. This would save roughly 35% of the energy input for the ethanol plant (Murphy and Power, 2008) and increase the biogas output dramatically. In Scenario 2, the ethanol plant produces 1,314 TJ of ethanol and no by-products. The biogas plant thereafter produces 464 TJ of biomethane in addition to digestate. Avoided products of the system include petrol and fertilizer.

Scenario 3 is similar to Scenario 2, however part of the biogas produced is used to replace fossil propane used in the ethanol plant for odor control (Paulsson, 2007); see Figure 7 where the exchange is denoted with a dashed line. The net output of biomethane is decreased to 438 TJ.

Scenario 4 is based on a further integrated Scenario 3. Instead of sending the stillage by truck, as in all aforementioned scenarios, a pipeline is assumed to connect the two plants and save transportation distances. A sensitivity analysis is also used to show the influence of the choice of energy systems. These include changing the CHP fuel to natural gas for process heat as often used in European plants (Börjesson,

2009) and changing the electricity system from the average Swedish electricity production system to the NORDEL[13] system (Ecoinvent, 2007).

5.1.2 Biofuel Industrial Symbiosis Network

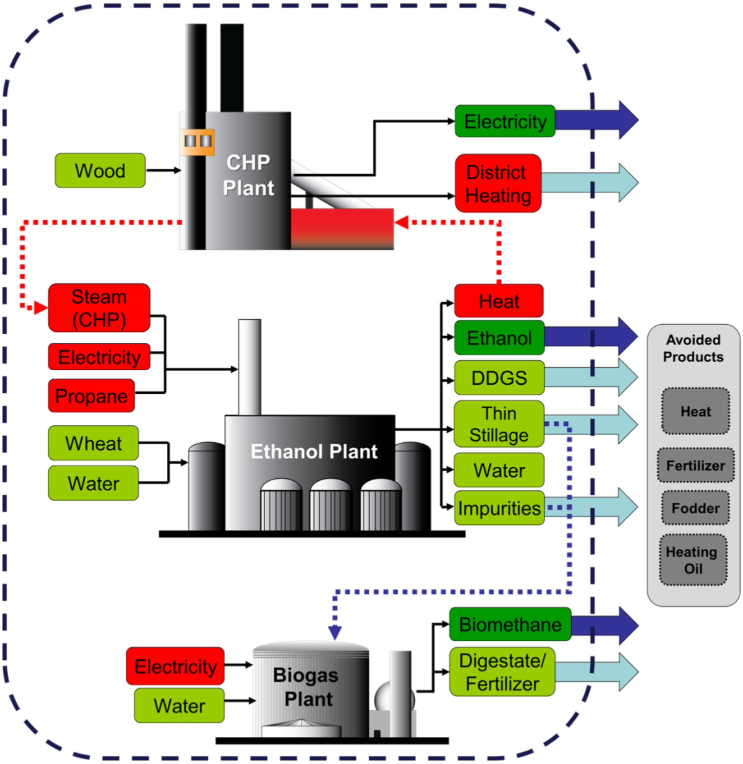

Figure 8: Description of Existing Scenario and System Boundaries. (Paper V)

Paper V reviews the environmental performance of an industrial symbiosis network based on data from Händelö. In the existing scenario, the ethanol plant delivers a fraction of the thin stillage to the biogas plant. Furthermore, the CHP plant provides steam to the ethanol plant; and thereafter the ethanol plant returns condensate heat back to the CHP plant. The existing IS network is compared with a reference scenario in addition to a fossil reference scenario to test for the sensitivity of the energy system in the reference case. The functional units are set for 1,314 TJ of ethanol, 38 TJ of biogas and 87 TJ of electricity from the IS network. Other products are

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[13] The NORDEL system from the Ecoinvent 2.2 database is used to represent the average electricity production in the Nordic countries. Swedish average electricity is also provided (Ecoinvent, 2007).

considered by-products and include DDGS, digestate, heat and impurities. More details can be found in Paper V.

The fossil reference scenario is created to compare with the existing case. The functional units of the system are the same as the existing scenario. However, in the reference scenario there are no exchanges of material or energy. Again, by-products of the system include impurities, digestate, DDGS and heating. In the reference scenario, the CHP plant is assumed to use wood-fired boilers similar to the existing scenario.

The fossil scenario is created to test the sensitivity to the energy system choice. The fossil reference scenario is comparable to the reference scenario described previously though fossil fuels are used. The CHP is assumed to use natural gas as fuel. Heat provided to the biogas plant is assumed to be produced from oil burners and it is assumed that the ethanol plant receives steam produced from natural gas boilers for process heat, as often used in European plants (Börjesson, 2009). Nonetheless, electricity is assumed to be provided by the Swedish electricity production system for all plants in the IS network and not from another system.

6 Biofuel Production Synergies: Existing and Potential Synergies

Given the many by-products produced by the biofuel industry and the abundance of organic by-products produced outside of the biofuel industry, there is potential for many exchanges to be established. This chapter will provide results from Papers I and II and describe some of the exchanges possible between biofuel firms and external industries.

6.1 Exchanges within the Biofuel Industry

From the description provided of the Händelö in Chapter 5 and Paper I, an example of an industrial symbiosis network in the biofuel industry is portrayed. Scenarios provided in Paper III explore further synergies which could be possible between the biofuel firms of Händelö. These include using all stillage for biogas production, biogas for flue gas treatment at the ethanol plant and the installation of pipelines for the material exchanges. However, the synergies also extend outside of IS network as several of the by-products are used in the agricultural sector, e.g. as biofertilizer and animal feed.

Worldwide many exchanges are possible in the biofuel industry. From Paper II, a total of 113 synergies were found in the literature which could be possible for the biofuel industry. Of the exchanges found between biofuel firms, i.e. between biogas, ethanol and biodiesel producers, 36 synergies were identified. Exchanges between ethanol and biogas producers are most prevalent. Many of the synergies identified included using ethanol by-products for biogas production, e.g. using stillage and other by-products for anaerobic digestion. Synergies also existed between ethanol and biodiesel producers, where ethanol by-products are used for biodiesel production, such as corn oil for biodiesel production. Synergies between the biodiesel and biogas industries were also present. Once again however, most of the synergies involved the use of biodiesel by-products for biogas production; e.g. glycerol and seedcake for biogas production.

6.2 Exchanges with External Industries

From the exchanges found in Paper II, exchanges between biofuel and external industries were most prevalent. A total of 83 synergies were found between the biofuel industry and external industries; the majority of which were exchanges where biofuel by-products were used for new products and services. Thereafter, many external industry by-products were found to have potential uses for biofuel production.

Paper II classifies and identifies these external industries, see Table 2. Of the external industries offering collaboration potential with the biofuel industry, the food and feed industry dominates the number of synergies found. Exchanges with the food industry consisted mainly of two types, 1) using biofuel by-products for human and animal food and feed, and 2) using food industry by-products for biofuel production. Many examples of these synergies exist including using DDGS for animal feed or additives to foods as well as using food industry by-products for biofuel production, such as waste vegetable oil for biodiesel production and dairy by-products for biogas and ethanol production.

Table 2: Industries interacting with biofuels for potential synergies (Paper II)

Category	**Number of Synergies**	***Examples***
Food/Feed	24	*Dairy wastes as biogas source*
Energy/Fuel	12	*Glycerol used as gasoline additive*
Chemical/Cosmetics	9	*Conversion of glycerol to glycolipids*
Municipal	9	*Waste heat from ethanol, biodiesel and biogas production used in swimming pools/swim halls*
Agriculture	8	*Sweet corn tassels from ethanol production used as replacement to peat moss in greenhouses*
Materials/Building	6	*Wheat protein, in aqueous ethanol, used for production of particle-bonding composites*
Algae	4	*CO2 from ethanol production used for algae for biodiesel production*
Environmental Services	4	*Biodiesel by-products used as carbon filters*
Greenhouse	4	*Carbon dioxide from biogas upgrading for greenhouses/plant source*
Forestry/Paper	3	*Biodiesel production from tall oil fatty acids*
Total	***83***	

Many other examples of using biofuel by-products for external uses were present. One example includes using biofuel by-products to produce energy, i.e. through combustion. Examples include glycerol and biogas digestate used in boilers. Glycerol, from biodiesel production has also been identified as a vehicle fuel and fuel extender in addition to use in the production of chemicals, including surfactants and glycollipids. A dominant synergy found in the literature is the use of organic material from, e.g. the agricultural and food industries for biogas production. Other synergies include using biofuel by-products for biofertilizer, filter media and dust suppressants. Waste heat from biofuel production has even been proposed for use in swimming pools and greenhouses. Carbon dioxide, a major by-product from biogas and ethanol production, has also been identified as a source for greenhouses, beverage industries and algae production.

6.3 By-product vs. Utility Synergies

From Paper II, the type of synergies, i.e. whether they are by-product or utility synergies, was also classified, see Table 3. Of the synergies identified, the majority are by-product synergies, where material is shared among firms. Most of the by-product synergies took place between biofuel and external industries. However, utility synergies were not as prevalent in the literature. Nonetheless they were identified between biofuel industries, where they included common infrastructure as well as heat and energy sharing between biofuel and external industries. Examples included using waste heat for further processing or use in algae production, greenhouses and swimming pools.

Table 3: By-product vs. utility synergies produced from literature review and brainstorming workshop (Paper II).

Method	**By-Product Synergies**	**Utility Synergies**
Biofuel→Biofuel	*26*	*4*
Biofuel→External	*46*	*6*
External→Biofuel	*30*	*1*
Total	***102***	***11***

7 An Approach to Quantify the Environmental Performance of IS Networks

Quantifications of the environmental performance in the IS literature are rare and lack methodological guidance. Based on a review of these previous quantifications, provided in Chapter 3.4, the following chapter provides an approach to quantify IS networks from Paper IV. A novel approach to distribute credits for avoided raw materials to firms is reviewed in addition to an approach to portray the benefits of being part of the IS network for firms involved in the exchanges.

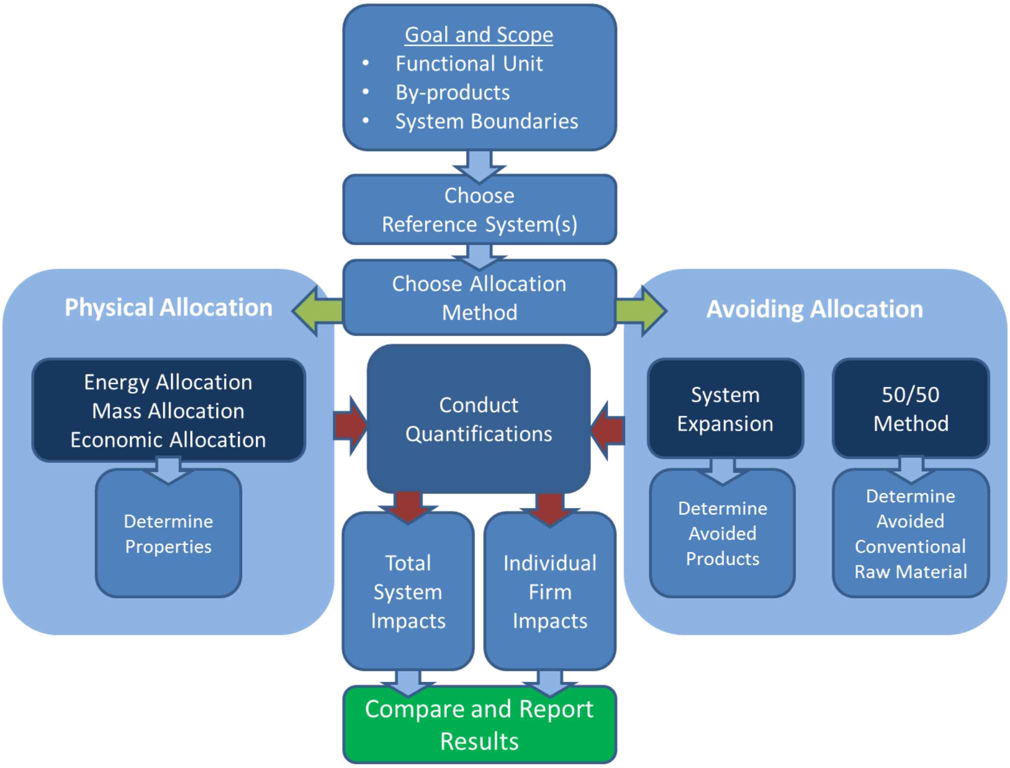

Figure 9: Overview of the Approach to Quantify IS Networks as described in Paper IV.

7.1 Goal and Scope

The quantifications of IS networks are recommended to follow ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b). At the minimum, environmental impacts such as the GWP (CO_2-eq) emissions should be accounted for. From Paper IV, the choice of functional unit is outlined. It was found in previous assessments that choosing the total output of the system may cause difficulties for comparisons as the outputs of the reference system may exceed those of the IS network. This can be overcome by viewing the IS network as a multi-functional system, which produces several main products and a number of by-products. The main products will be the determining products of the system which define the output of the respective by-products. By-products are thus dependent upon the main products and are allocated impacts or credits from the avoidance of processes, if they and are fully utilized in other processes (Weidema, 2001). Once the main products are chosen, and assigned as the functional unit of the system, the by-products can then be labeled.

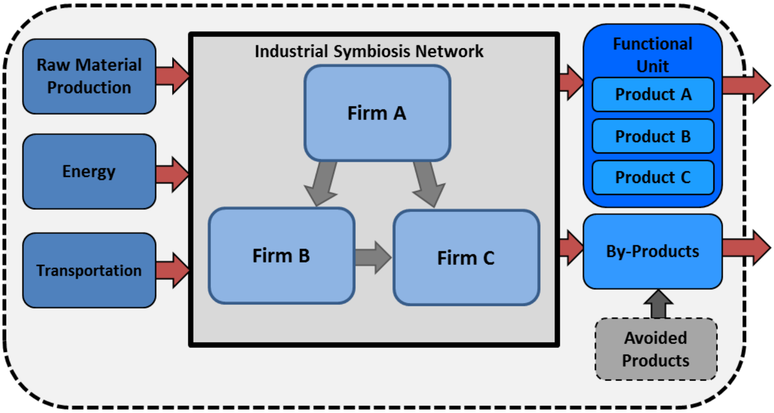

Figure 10: System boundaries of the assessment (Paper IV).

The system boundaries of the IS network, as outlined in Paper IV, should cover the upstream impacts from the use of raw materials, transportation and also include the impacts created by the IS network. In LCA terms, the quantification should cover at least a “cradle-to-gate” perspective. Using this boundary will allow for the IS network to be compared to other scenarios and possible changes to the system. Furthermore, by-products, and avoided impacts from their use, are also included in the assessment; see Figure 10.

The choice of reference system is influential for the results. Although these are only speculative representations of the system without exchanges, they can be created to provide further transparency and test for the sensitivity to choices. This system should be chosen based on characteristics of the region, e.g. typical fuels for energy system provider. In order to allow for the comparison with the existing scenario, the reference scenarios or other scenarios must use same functional unit as the existing scenario. It is recommended that further reference scenarios be modeled to account for changes in the energy systems (Weidema et al., 1999; Ekvall and Weidema, 2004; Wolf and Karlsson, 2008). Furthermore, it is not known whether by-product streams would be optimized, substituted, etc. and therefore consideration should be made for by-product stream changes and optimizations when possible. By choosing several reference systems, a sensitivity analysis for the life cycle assessment of the industrial symbiosis network will be accomplished for different assumptions made in the assessment.

7.2 Partitioning Impacts and the 50/50 approach

Since the IS network produces several main products, in addition to by-products, the impacts must be partitioned between all the products of the system, which can take place by physical allocation methods or by using methods to avoid allocation. Both methods are recommended in the approach of Paper IV to show the influence on the results.

System expansion can be used for the assessment, for which impacts from avoided conventional products are deducted from the impacts to the functional units. The choice of avoided conventional products presents some difficulties and a comprehensive review should be undertaken to identify these products; see e.g. Weidema et al. (1999) and Ekvall and Weidema (2004). The system expansion approach is recommended to be conducted similar to the approach of Weidema (2001) for multi-functional systems and exchanges.

Nonetheless, the system expansion approach outlined by Weideman (2001) to avoid allocation, may not distribute the benefits from the exchanges to the firms involved. In order to distribute the impacts to the firms involved in the exchange a new approach was created in Paper IV to proportionately distribute the impacts between firms involved in an exchange. The approach allows for crediting both firms with an avoided conventional raw material due to the exchange. This crediting approach draws inspiration from literature on open-loop recycling, which takes into account supply and demand to encourage recycling and exchanges and allows impacts to be split between the consumer and handler of a recycled product. This new approach is referred to as the 50/50 method in this thesis and in Papers IV and V. The method is described further in subsequent text and in Paper IV.

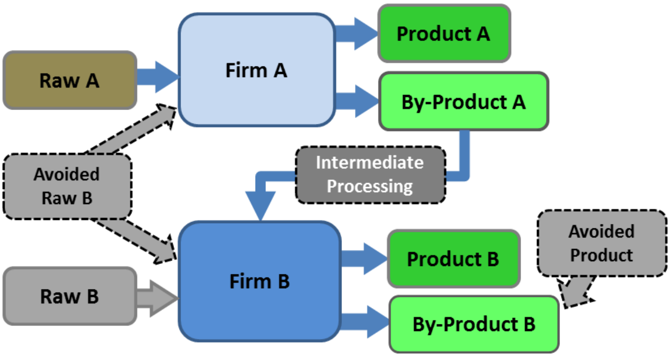

Figure 11: Illustration of the 50/50 method, including possible intermediate processing and avoided raw materials and products, for the exchange of By-Product A between Firm A and B (Paper IV).

As outlined in Paper IV, the 50/50 method can be used to further allocate credits for the products exchanged between firms of an IS network. Figure 11, above, illustrates this with an exchange between Firms A and B. In order to fairly distribute the credit from the avoidance of Raw B, Firm A and B would both receive 50% of the credit for the equivalent amount of Raw B avoided. However, in order to not double-count the benefits and to model changes to the system by removal of Raw B, Firm B would still receive the impact for the production of Raw B. Therefore, Firm B would only receive 50% of the impact of Raw B in total. Furthermore, by-products leaving the system are still avoided, as described in the system expansion method. Intermediate processing is also possible, and the impacts of such a step are to be distributed between the firms involved in the exchange following the same 50/50 logic.

Physical allocation may also be used to allocate impacts between the products and by-products using physical parameters. The physical parameters may include e.g. energy, economic, mass or exergy allocation. As many LCA studies use either energy or economic allocation, it is recommended that these parameters be used. Using physical allocation to partition the impacts allows By-Product A to enter Firm B with a share of the impacts from Firm A; see Figure 11. Firm B therefore accepts some of the impacts of producing By-Product A. Using physical allocation as such is similar to an approach provided by Ekman and Börjesson (2011) for a biorefinery process.

From the method produced, it is possible to find the total impacts from the IS network in addition to the impacts for individual firms of the symbiosis; though the quantification for each firm requires additional steps. Upon calculating the impacts for the main products for the scenarios, e.g. the reference, existing or improved scenarios, using any of the aforementioned allocation methods, the impacts can be compared to provide the net benefit of the IS network.

To find the impacts for each firm in the IS network, the assessment should be conducted for each main product separately. Thereafter, to find the benefit for individual firms, a comparison is conducted for the existing scenario and the reference or improved/expanded scenario. The net benefit of the IS network will furthermore be equal to the sum of the net benefits of the main products. See Paper IV for further details on approach.

8 Environmental Performance of Industrial Symbiosis in the Biofuel Industry

This chapter provides the results from environmental performance quantifications of IS networks in the biofuel industry. Results from Paper III will first be presented, where scenarios for increasing integration between an ethanol plant and biogas plant will be tested. Thereafter, results from Paper V are presented, using the approach outlined in Paper IV, to show the total IS network impacts in addition to impacts and benefits for the firms of the IS network.

8.1 Environmental Performance of Co-located Ethanol and Biogas Plants

From Paper III it was found that co-located biogas and ethanol plants have the possibility to improve their environmental performance through by-product and utility exchanges. The results show that increasing integration, i.e. the amount of stillage exchanged and the number of exchanges, has the potential to provide improvements for the greenhouse gas emissions and can be concluded for both the energy allocation and system expansion methods; see Figure 12. A slight improvement can be seen when comparing the reference scenario to the existing scenario. Thereafter, compared to the existing scenario, Scenario 1 also had a slight improvement. A large reduction is seen when all stillage is used for biogas production, i.e. in Scenarios 2-4. However, in Scenarios 3 and 4, no significant improvements can be seen for further integration compared to Scenario 2 by using biogas for emissions control and building a pipeline to distribute the stillage between the ethanol and biogas plants.

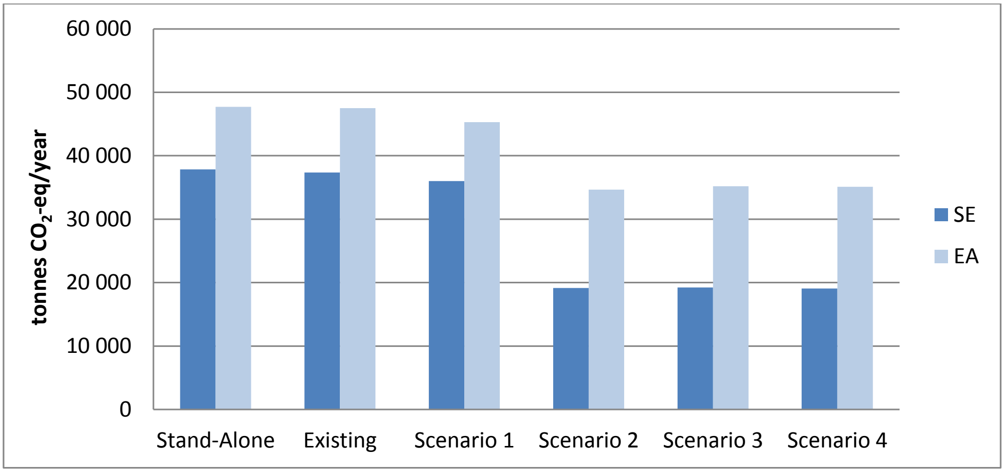

Figure 12: Greenhouse gas emissions for all scenarios using the System Expansion method (SE) and Energy Allocation method (EA), measured in tonnes CO_2-equivalent/year (Paper III).

Although there may be reduced greenhouse gas emissions for the co-located firms for increased integration, it is possible that increases in integration may cause increased eutrophication and acidification impacts; see Figure 13 and Figure 14. When the integration is increased, there is a significant increase in the amount of biofertilizer produced from the system, and less production of fodder. It can be determined that the avoidance of fodder provides more benefits than the avoidance of conventional fertilizers thus leading to increasing eutrophication and acidification impacts using the system expansion method. The energy allocation method however, shows reduced acidification and eutrophication impacts for increased integration. This is primarily due to the fact that with increased integration, the output of biofertilizer from the system increases. Although the biofertilizer is not used as an energy product, it receives a large share of the impacts, and thus less impact is given to the functional unit, leading to a reduction in eutrophication and acidification impacts.

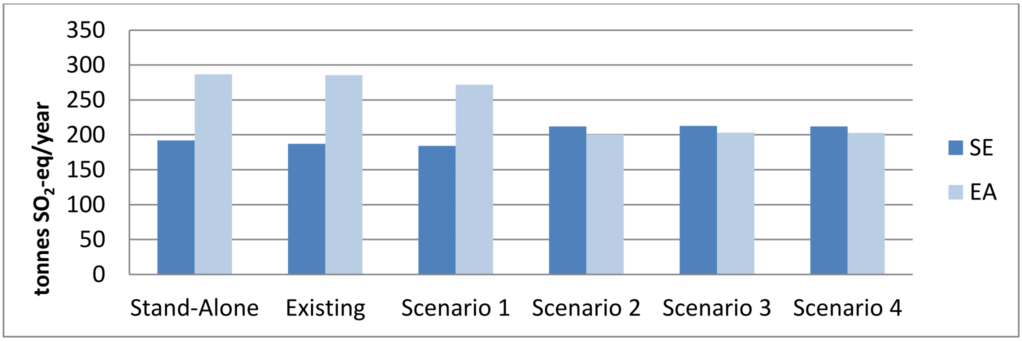

Figure 13: Acidification potential for all scenarios using the System Expansion method (SE) and Energy Allocation method (EA), measured in tonnes SO_2-equivalent/year (Paper III).

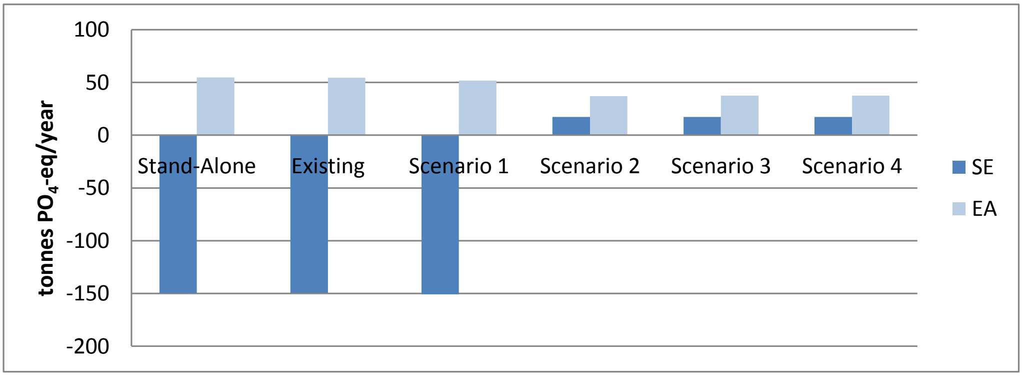

Figure 14: Eutrophication potential for all scenarios using the System Expansion method (SE) and Energy Allocation method (EA), measured in tonnes PO_4-equivalent/year (Paper III).

From the analysis of the impacts from Paper III, the most influential processes for the environmental performance of the system include the cultivation of grains, conventional fodder replaced, conventional fertilizers replaced, process heat, electricity network and transportation of materials. As the current system uses biomass for process energy, a sensitivity analysis was conducted to identify the influence of different electricity and heating systems for the integrated biogas and ethanol plants. The NORDEL electricity network was exchanged for Swedish average electricity production in addition to the process heat obtained from natural gas, in place of biomass. The results show that heating substantially increases the impacts of the system, while the electricity network increases the emissions slightly for all scenarios; see Figure 15.

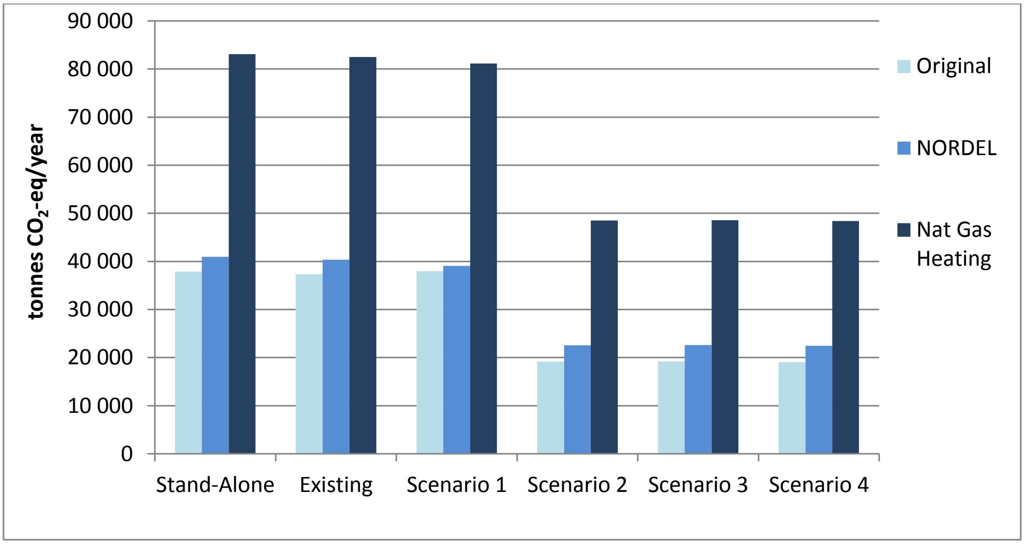

Figure 15: Sensitivity analysis for the scenarios using system expansion method for energy system changes, measured in tonnes CO_2-equivalent/year (Paper III). *Original-Original data with biomass energy system and Swedish electricity system, NORDEL-Scenarios tested using NORDEL electricity system, Nat Gas- Heat supply from natural gas CHP.*

8.2 Environmental Performance of a Biofuel IS Network

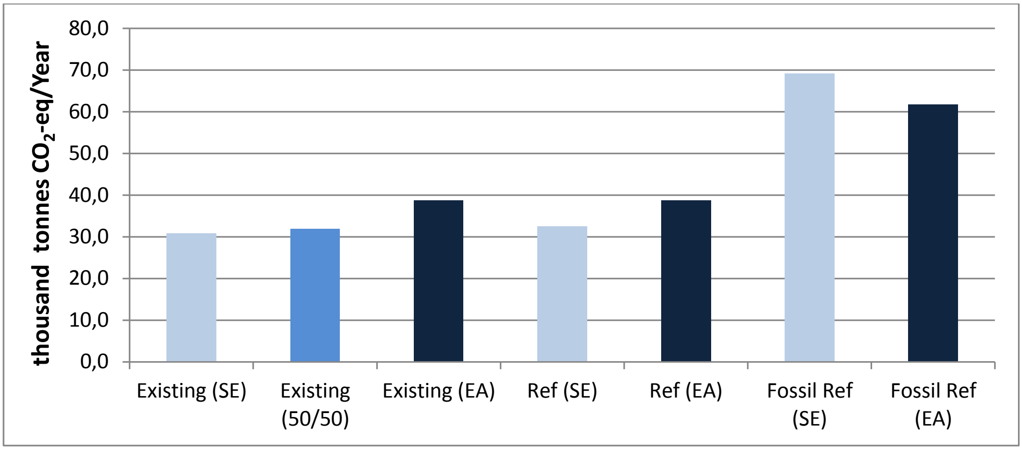

Figure 16: Total Impact of Existing and Reference (Ref) Scenarios, measured in thousand tonnes CO_2-eq/year using the System Expansion (SE), Energy Allocation (EA) and 50/50 method (Paper V).

Paper V shows that the entire IS network may have reduced impacts compared to reference systems where no exchanges are present. However, the benefits depend on the choice of reference system and method for handling the by-products. For example, in the system expansion method, a total benefit of 0.7 and 37.4 thousand tonnes CO_2-eq annually were found when comparing the existing scenario to the reference scenario and fossil reference scenario respectively; see Figure 16. However, using energy allocation resulted in no benefit when comparing the existing scenario with the reference scenario, though a benefit of 23 thousand tonnes CO_2-eq annually compared to the fossil reference scenario.

Table 4: Individual Impacts for the Ethanol, Biogas and CHP plants, measured in thousand tonnes CO_2-eq/year (Paper V).

	Existing Scenario (SE)	**Existing Scenario (50/50)**	**Existing Scenario (EA)**	**Reference Scenario- (SE)**	**Reference Scenario (EA)**	**Fossil Reference Scenario (SE)**	**Fossil Reference Scenario (EA)**
Ethanol	29.6	30.4	37.6	30.5	37.6	60.6	57.5
Biogas	0.9	0.3	0.8	1.8	1.0	2.0	1.1
CHP	0.3	1.2	0.4	0.3	0.2	6.6	3.2
Total	*30.8*	*31.9*	*38.8*	*32.5*	*38.8*	*69.2*	*61.8*

Furthermore, Paper V shows that the impacts and benefits of the IS network are not equally partitioned between the firms and depends on the allocation method used. Using the system expansion method, a benefit of 0.9 thousand tonnes CO_2-eq annually was presented for both the ethanol and biogas plants, while the CHP plant received no benefit. However, if the results are compared to the fossil reference scenario, benefits of 31, 2.4 and 6.3 thousand tonnes CO_2-eq annually were seen for the ethanol, biogas and CHP plants respectively.

Using the energy allocation method, when comparing the existing scenario with the reference scenario, no benefit was found for the ethanol plant. The biogas plant however received a benefit of 0.2 thousand tonnes CO_2-eq annually and the CHP plant had greater impact than the reference CHP plant, having an increase of 0.2 thousand tonnes CO_2-eq annually. If the results were compared with the fossil reference scenario, the ethanol plant received a benefit of 19.9, the biogas plant a benefit of 0.3 and the CHP plant a benefit of 2.8 thousand tonnes CO_2-eq annually; see Table 4.

Table 4, provided the impacts for firms of the IS network. It can be observed that the system expansion method led to larger benefits for the CHP plant, due avoidance of all impacts for heat delivered to the ethanol plant. In the 50/50 method however, the benefits of this exchange were split between the firms of the IS network equally. Furthermore, in the system expansion method, the ethanol plant received a larger benefit due again to all impacts of avoided wheat being deducted for the exchange of stillage to the biogas plant. Using the energy allocation method, each plant receives a share of the impacts from the exchange of by-products and utilities. This share received is based on the share of energy output from each plant, which is partitioned among the products and by-product of each respective plant.

By using the 50/50 method and comparing the results to the reference scenario using the system expansion method provided a benefit of only 0.1 thousand tonnes CO_2-eq annually for the ethanol plant. Furthermore, the biogas plant had a 1.5 thousand tonnes CO_2-eq benefit annually while the CHP plant increased its impact by 0.9 thousand tonnes CO_2-eq annually. Comparing the existing scenario with the fossil scenario yielded a benefit for the ethanol plant of 30.2, a benefit for the biogas plant of 1.7 and a benefit for the CHP plant of 5.4 thousand tonnes CO_2-eq annually; see Table 4.

Table 5: Major impacting processes for the entire system (IS network for the existing and all plants for reference cases, measured in thousand tonnes CO_2-eq/annually using the *System Expansion Method (SE), Energy Allocation Method (EA) and 50/50 method (50/50).*

Process	**Existing Scenario (SE)**	**Existing Scenario (50/50)**	**Existing Scenario (EA)**	**Reference Scenario- (SE)**	**Reference Scenario (EA)**	**Fossil Reference Scenario (SE)**	**Fossil Reference Scenario (EA)**
Wheat	56.9	56.9	34.5	58.1	34.4	58.1	34.4
Transportation	2.8	2.8	1.7	2.8	1.7	2.8	1.7
Heat	0.8	1.8	1.2	1.8	1.2	35.8	23.0
Electricity	1.1	1.1	0.7	1.1	0.6	4.3	2.1
Methane	0.0	0.8	0.3	0.8	0.4	0.8	0.4
Fertilizer	-2.7	-2.7	0.0	-2.0	0.0	-2.0	0.0
Fodder	-29.3	-29.3	0.0	-30.4	0.0	-30.4	0.0
Other	*1.2*	*0.5*	*0.4*	*0.4*	*0.5*	*-0.2*	*0.2*
Total	*30.8*	*31.8*	*38.8*	*32.5*	*38.8*	*69.2*	*61.8*

Results from the system expansion method led to a slight benefit in the comparison of the existing and reference scenarios due to an increase in the use of wheat for biogas production in the reference case; see Table 5. It can also be identified that the existing scenario obtained a larger benefit for avoided fertilizers compared to the reference scenario, though the reference scenario saw a larger benefit for the avoidance of conventional fodder, as the reference scenario produces more fodder production when no integration is employed. In the fossil reference scenarios a large increase in emissions was identified, due to the use of fossil energy for the heating supply and electricity. From the energy allocation method, no clear process led to the existing and reference systems having similar impacts. However, once again a large increase of emissions was observed in the reference fossil scenario.

Table 6: Impact from using various conventional raw materials for biogas production, including transporation of the raw materials, measured in thousand tonnes CO_2-eq/annually.

	Wheat	**Manure**	**MSW**
Impact from Conventional Raw Material	1.25	0.04	0.22

Paper V also presents an analysis and discussion of the importance of the choice of conventional raw material replaced by an exchange of by-products and utilities. Wheat was chosen in Paper V as the conventional raw material in biogas plants. However, if the choice was made to use another material, e.g. manure or municipal solid waste (MSW), the avoided impacts would have changed; see Table 6. Furthermore, a change as such would lead to changes in the quality of biofertilizer, transportation distances and other impacts associated with the conventional raw materials, which must be accounted for; Table 6 provides only the impacts from the processes used to cultivate (or collect) and transport the materials.

9 Discussion

In this chapter, an evaluation and discussion of the results will be presented relating to the research questions of this thesis.

9.1 Collaboration with the Biofuel Industry

9.1.1 Exchanges between Biofuel Firms and External Industries

With the abundance of organic by-products produced from biofuel production firms, there are many opportunities for collaboration. Between biofuel firms, by-products can be shared and used for increased biofuel production due to the organic nature of the materials. However, the majority of the synergies provided outline the use of biodiesel and ethanol by-products for biogas production. Biogas production can be therefore introduced to ethanol and biodiesel plants to make use of by-products. The biofuels may also be used as raw material for further processing. An example includes using ethanol in place of fossil methanol for biodiesel production (Quintella et al., 2012) and biogas for process energy or flue gas odor control.

Synergies with external industries also offer many opportunities, and are the predominant synergies identified in Paper II. Exchanges with external industries may be a relevant option to allow biofuel firms the possibilities to broaden their raw material base and allow external industries to benefit from biofuel by-products, in addition to providing the biofuel industries with by-products as raw materials. These synergies would furthermore allow the biofuel and external industries to obtain economic and environmental benefits. The food industry was recognized as a potential partner with biofuel firms. Biofuels may use by-products from the food industry for their raw materials, and alternatively the food industry may use biofuel by-products (Nayono et al., 2010; Hong and Yoon, 2011). Current focus is on the linear flow of food crops into the biofuel industry, without regard to by-products and the synergistic possibilities created between the industries. As such, these symbiotic relationships have implications for the current food versus fuel debate (Srinivasan, 2009). Other interesting partners include the energy providing industries as well as chemical industries. Biofuel by-products have many uses outside the biofuel industry. Glycerol, for example, can be used for cosmetics, fuel extenders, surfactants and glycol-lipids (Kiatkittipong et al., 2010; de Sousa et al., 2011; Liu et al., 2011b).

While many of the aforementioned exchanges are by-product synergies, utilities synergies are rarely discussed. Similar findings were recorded in an Australian case where exchanges of wastes and by-products dominate the synergies involved between industries from their studies of global synergy projects (CECP, 2007). Nonetheless, utilities synergies have been shown to have a large influence on the environmental performance of a system, as shown in Papers III and V. In the biofuel industry, this can be recognized in several studies where the energy system used has a large influence (Eggeman and Verser, 2006; Murphy and Power, 2008; Börjesson, 2009).

Of the synergies found, synergies with biogas production have been a predominate addition to both biofuel firms and external industries. By converting by-products and wastes from other firms into methane in addition to a biofertilizer, biogas plants can offer many industries a means to “upcycle” their wastes; see Paper I. Therefore, biogas producers have the possibility for co-location or collaboration with many industries as a “drop-in” for other plants to provide added value to the by-products or waste and obtain an energy source at the same time. As an example, biogas production takes many wastes from the food industry which is difficult to dispose of, e.g. slaughterhouse wastes and dairy wastes. In the past, these wastes were an economic burden to the food industry and were taken care of by combustion or waste water treatment. Before the anaerobic digestion takes place the materials go through a homogenization treatment; thereafter they can be used as a sustainable fertilizer (Nayono et al., 2010; Svensk Biogas AB, 2013b). This may suggest that biofuel production from waste, with valuable by-products, may lower the entropy of the products or at least make use of what entropy is left; see e.g. (Georgescu-Roegen, 1971; Ayres, 1998; Martin and Parsapour, 2012).

9.1.2 Implementation of Synergies

From Paper II, an understanding of potential collaborations with the biofuel industry was outlined, including a classification of the distinctive industries. This information can be useful to develop potential business partners to allow new synergies to be established (Bossilkov and Lund, 2008; Eckelman and Chertow, 2009) within and outside the biofuel industry for new markets and improvements in environmental and economic performance. Collaboration may therefore take place through the exchanges of material and energy and offer possibilities for co-location. However, co-location is not essential for by-product exchanges (Jensen et al., 2011; Lombardi and Laybourn, 2012), though extended detachment may undermine the economic and environmental performance improvements. By-product exchanges in the biofuel industry are commonly distributed over long distances, examples including the market for DDGS and glycerol. Nonetheless, materials are best suited for shipping in their dry form and the shipment of water is not optimal (Patterson et al., 2011; Alburquerque et al., 2012; Poeschl et al., 2012). Although by-product exchanges do not necessarily require co-location, utility synergies may require co-location and therefore limit the number of possible synergies between industries.

From previous research related to finding possible synergies between industries, it has been determined that the implementation of synergies offers numerous challenges. According to the Centre of Excellence in Cleaner Production (CECP, 2007) the success of the implementation of synergies depends on several factors, of which the failure to meet them inhibits the success of the synergies. These factors include e.g. a plausible business case with outlined opportunities to reduce costs and secure resources, a license to operate with the synergies and technology availability to allow for the realization of the synergies. Furthermore, other factors may also determine the success of the synergies. The availability of local markets, regional conditions and seasonal fluctuations in material availability may influence the implementation of the synergies. For example, while biogas was found to be a relevant synergy with many other firms, in the biogas industry the use of biogas and the handling of digestate can be seen as bottlenecks to further development (Alburquerque et al., 2012) and may inhibit the development of more biogas plants (Lantz et al., 2007). Wolf (2007) also describes how "human factors" may also influence the implementation of synergies, where trust, positive attitudes and willingness to undertake such a project are crucial to their implementation.

9.2 Quantifying Industrial Symbiosis Networks

Attempts to quantify industrial symbiosis networks are limited in the literature and have furthermore lacked structured methods and guidelines. Additionally, the quantifications available have primarily viewed only the impacts occurring for the IS network, thus ignoring upstream impacts. Sokka (2011) argues that quantitative life cycle based methods are needed to assess the environmental relevance of particular flows. The approach provided in Paper IV therefore addresses many of the methodological concerns from the previous attempts using life cycle assessment as a background. However, although the method attempts to address methodological concerns, it also has its limits, similar to all LCAs.

As Sokka (2012) describes, process based LCAs, as outlined in Paper IV, may not address all environmental impacts and that a large share of the emissions may not be modeled; anywhere from 10-20% of the IS network emissions. However, in biofuel production a large share of the impact comes from the agricultural inputs. It was assumed that the agricultural inputs were kept the same in the reference case, and thus since the aim of the model is to assess the improvement possibilities, further impacts using e.g. hybrid methods were not deemed relevant. Furthermore, the method in Paper IV does not necessarily exclude the use of further upstream impacts with e.g. input-output methods, and therefore hybrids could be produced.

Although the approach outlined in Paper IV may provide some guidance, it may not be applicable in all IS networks to answer all research questions. The approach is therefore best suited to quantify the total impacts of an industrial symbiosis network in addition to portraying the impacts for individual firms of the IS network. Using the results from scenarios, a comparison can then be made and used to show how the results are influenced by certain exchanges.

In order to give credibility, the approach should be applied in other cases of IS networks as it could be argued that it was designed for the study of biofuel industrial symbiosis networks an in an illustrated example of the paper; the subject of the authors. However, Paper IV was designed to outline a generic case for IS networks and therefore is applicable in other industries, though some modifications may be warranted.

The method also allows for different choices of allocation methods, or avoidance thereof, in the assessments. Information is provided on some critical choices when choosing these methods. Yet again however, the choice of allocation is highly controversial and there is no correct way to solve the problem (Ekvall and Finnveden, 2001; Guinée et al., 2004; Wardenaar et al., 2012), though the method provided in Paper IV recommends the use of both system expansion modeling and physical in order to show the influence they have on the results.

Paper IV also outlines the use of the 50/50 method which can be seen as an example of an approach to split the impacts between producers involved in an exchange. As such this choice may also introduce some discussions about its usefulness. As the method was designed to promote exchanges, it may not be useful when exchanges cause impacts instead of benefits to the firms. Examples are provided in Papers III and V, where the exchanges may cause net impacts when comparing an existing system to a reference system. Furthermore, distribution of impacts may not be warranted for exchanges of products classified as wastes. Furthermore, in the 50/50 method the choice of avoided conventional product may be difficult as rarely the products are mono-functional, i.e. part of another process (Heijungs and Guinée, 2007).

Previous guidance has also been developed for the quantification of industrial symbiosis. Matilla et al. (2012a) provide recommendations for these quantifications. However, the method is not entirely applicable in this study as the aims of their study differ and the focus is upon quantifying the total impacts of the IS network. Although not entirely compatible, the methods offer compliments to one another. Using the outline of Matilla et al. (2012), provides an approach complimentary to Paper IV to decide on the type of modeling needed for decision support if the design of the IS network is to be planned, which for Paper IV did not include consequential modeling though system expansion was recommended. However, the recommendations from the method presented by Mattilla et al. (2012) on the choice of functional unit may not provide useful information for firms of the IS network as the functional unit is set to the entire output of the IS network. Once again, as suggested by Lombardi and Laybourn (2012), collaboration is initiated by self-interest and not entirely motivated by reduced impacts of the IS network. Nonetheless, the choice made in Paper IV to set the functional unit as the main products of the system may also prove difficult to accomplish when modeling the reference scenarios, which should have the same functional unit. This can be the case if the reference system chosen was modeled to optimize outputs and may not produce the same products and by-products as the existing case. A requirement is that the reference system has the same firms as the existing case, which may not necessarily be the case if no symbiotic activity was in place; however in order to model the differences this is required.

9.3 Environmental Performance Improvements using IS in the Biofuel Industry

Results from this study show that the environmental performance of an IS network may lead to improved environmental performance in the biofuel industry. From Papers III and V, comparisons to reference systems show reduced impacts in the IS network. Sokka et al. (2011), Wolf and Karlsson (2008) as well as Jacobsen (2006) provide similar results, showing that the IS network has a reduced impact compared to the reference systems.

However, it is also identified in Papers III-V that the choice of reference system may greatly influence the results of the study. In Paper III the energy system was changed in a sensitivity analysis to account for the use of NORDEL electricity and natural gas in place of Swedish average electricity and renewable energy. As such, the emissions were increased by 8% and 120% respectively to the reference system. Alterations to the energy system, for example, can prove influential for the results. Similar results were found in a study by Sokka et al. (2011) where several reference systems were compared, leading to large differences.

As mentioned by Sokka (2011) and van Berkel (2010) the choice of reference system is speculative and may not fully model the stand alone case. The choice of reference system is often difficult and depends on a further understanding of regional conditions and the typical systems used in the industry, both locally or globally. In Paper V, the use of fossil fuels for process energy in the biofuel industry was chosen as fossil systems for energy are common throughout Europe and the USA (Börjesson, 2009), though renewable energy systems are more typical in Sweden. As such, the reference systems using renewable energy do not have a large increase in emissions in relation to the IS network being studies. In previous assessments from the Finnish forest industry, the choice of reference system has also proven difficult. This is due to the fact that symbiotic operation and renewable energy are common (Sokka, 2011). As provided in Paper V, the choice of conventional products used for production processes may also have a large influence. While wheat was chosen for the reference substrate for biogas, a large portion of substrates for biogas production is provided by wastes from the food industry, agriculture and municipal wastes in Sweden (Lantz et al., 2007). Furthermore, altered flows for by-product streams or provisions for system optimization were not considered in the appended papers, e.g. different uses for stillage or biogas digestate. Nonetheless, Van Berkel (2010) recognizes that these system optimizations could be important to model for the speculative reference scenarios, possibly reducing the impacts.

The largest impacts found in this research have resulted from the agricultural inputs, with the majority of the impacts from the input of wheat for ethanol production. Similarly, Sokka (2011) found that upstream impacts represent a large portion of the life cycle impacts. To capture a larger extent of the upstream emissions, Mattila et al. (2010) use hybrid-LCA analysis with input-output data. In the appended papers however, input-output methods were not applied. As mentioned previously from the approach provided, the use of hybrid methods is not rejected as a possible addition to the data. However, as the upstream emissions for the current IS network came primarily from the use of wheat in the existing and reference cases, with the bulk of the impacts for raw materials from the ethanol plant, the use of hybrid methods may not provide useable results for the comparisons of different designs for IS networks as in Paper III. Furthermore, Ekvall et al. (2007) claim that LCAs entail drastic simplifications of complex realities and should focus on the parts of the system expected to be affected by changes in order to stay within the confined budgets and time constraints of the project.

The direct emissions from the IS network did not represent a major share of the emissions in the existing scenarios. These emissions would primarily be associated with the CHP plant. However, the CHP plant did not account for a large share of the direct emissions from the IS network. Sokka (2011) found that the CHP plant in the forest IS network accounted for roughly 40% of the direct emissions of the IS network, though it accounted for only 14% of the total emissions. The results from this study were therefore different, as the emissions of CO_2 from the ethanol, biogas and CHP plants were not accounted for. This was due to the fact that biogenic carbon was not included in the EPD2008 method, although emissions of methane were considered. Scenarios in Paper III also reviewed the use of incremental changes to the IS network toward more sustainability, including using biogas in place of propane for flue gas odor control and using pipelines to transport the thin stillage.

However, although these amounted to environmental performance improvements, their benefit was overshadowed by the upstream impacts of the IS network.

Jacobsen (2006) states that IS exchanges are only one element used for improving the environmental performance of the companies and should be considered as part of the process to reduce the total environmental impacts. In accordance, Sokka (2011) states that it is important to avoid shifting problems through the promotion of industrial symbiosis. From the results, it has been found difficult to balance the environmental performance globally and locally. While the emissions of greenhouse gases may be reduced through exchanges in an IS network, there is a potential for increased emissions on a local scale, though not necessarily close to the IS network. It has been found in Paper III that the acidification and eutrophication potentials may increase, depending upon the choice of allocation method and the extent of the integration. For example, by removing the production of DDGS as an animal fodder from the system in Paper III for biogas production, the use of an alternative fodder, i.e. soy meal and barley, may increase the eutrophication and acidification impacts. This may shift the problems to other areas, such as South America, where a large expansion of soy has been seen (Tomei et al., 2010).

It is also important to understand that the allocation method used may significantly influence the results of the study. Results from this research show that significant dissimilarities can be seen in the results for physical allocation and system expansion. For instance, in Paper V, the emissions for the reference scenario and existing scenarios were roughly 20% higher using the energy allocation method compared to the system expansion method. In biofuel systems, this has been identified by several authors as one of the most influential factors for divergent results from LCAs of biofuels (Börjesson, 2009; Cherubini et al., 2009; Cherubini et al., 2009; van der Voet et al., 2010; Cherubini et al., 2011). The different allocation methods also led to the impacts and benefits from exchanges being portioned between firms of the IS network to varying degrees. These differences thus show the influence the allocation method may have. As such, by reviewing how the methods may influence the results of the IS network quantifications, the IS community may gain further transparency by addressing and validating the uncertainties of methodological choices.

However, despite the improvement possibilities of using IS in the biofuel industry, as quantified in this thesis and appended papers, the results cannot lead to a conclusion of which system is "better." However, according to Finnveden (2000), the quantifications can be used to increase the knowledge to influence processes which may cause large impacts, which may be especially useful for studies of improvements in the IS network.

9.4 Contributions of this study to Biofuel and IS communities

Using concepts from industrial symbiosis may offer many benefits for the biofuel industry. From IS, biofuel systems can gain insight for energy and material flow optimizations.

Furthermore, synergies are also abundant outside the biofuel industry where biofuel production by-products can be used further as well as external industry by-products as biofuel raw materials. By finding increased valorization, the biofuel industry may alleviate dependencies upon subsidies (de Gorter and Just, 2009). Both within and outside the biofuel industry the use of IS concepts may also lead to viewing biofuel systems in a system perspective, instead of the typical linear input-output model, where biofuels can benefit from using wastes and providing valuable by-products and energy exchanges.

Additionally, the industrial symbiosis literature may gain insight from the biofuel industry. From this thesis, the description and representation of the renewable energy based IS network of Händelö, Sweden offers the IS community an example of a renewable energy based system. Karlsson and Wolf (2008)and Sokka (2011) also provide examples of renewable IS networks in the forest industry. Examples based on renewable energy are welcomed additions to the field. This is important as many symbiosis networks differ from one another, making them hard to compare (Sokka, 2011). Many of the popularly cited symbiosis networks are based on fossil systems, e.g. Kalundborg, Denmark and Guayama, Puerto Rico (Chertow and Lombardi, 2005; Jacobsen, 2006), thus questioning the sustainable perception of the IS concepts.

The benefits of the method extend beyond portraying the net benefits for the entire IS network. Benefits for the individual firms offer many implications for the research community and industrial sectors. Wolf and Karlsson (2008) identified that the benefits gained from IS networks may be important to firms for taxes, subsidies, marketing and environmental consent. When firms must meet guidelines based on limited greenhouse gas emissions through environmental performance reporting, this can be especially important. Such is the case in the biofuel industry where the EU-RED (European Union, 2009b) mandates that all biofuel producers deliver such environmental performance reports, in addition to other reports on land use and product certifications, in order to receive tax incentives. By receiving benefits for avoided conventional products through the exchange of material and energy, the mandates may be met for increased greenhouse gas emissions reductions in the future. However, methodological aspects of the assessment methods provided by the EU-RED may not allow for benefits of combined production and outlines the use of energy allocation for the calculations. Using energy allocation as outlined in the EU-RED may lead to issues when by-products are not used as an energy source, e.g.

fertilizers, and may even lead to by-products being modified solely for energy purposes.

Information provided by the method may also be used for facilitating industrial symbiosis for business relations, optimization of processes and communication of environmental performance of firms. Strategic decisions may also be influenced by the results of showing the benefits or impacts of being part of an IS network, where the environmental performance of the firms may be compared with economic aspects of the exchanges. For instance, exchanges may be warranted to meet regulations even if the economic incentives of the exchanges provide little income, but the environmental performance is improved. Contrary to this, exchanges may also be removed if shown not to provide much benefit to the company even though they may lead to improvements for one of the firms involved in the exchange. Again, Wolf and Petersson (2007) state that information on the benefits of the synergies can be important for the implementation and the success of the synergies. However, industrial symbiosis and industrial ecology may not always lead to benefits to the firms, economically as the attention is on the exchange of material and energy, which may not contribute to competitiveness in the corporate setting (Esty and Porter, 1998).

Firms may even be able to promote how the exchanges offer benefits and improved environmental performance in their marketing (Leonidou et al., 2013). In the biofuel industry this is welcomed, as again biofuels are heavily criticized. Examples of how IS has been marketed include examples such as Kalundborg (Grann, 1997) and even Händelö (Cleantech Östergötland, 2009; E.ON Värme Sverige, 2009; Lantmännen Agroetanol AB, 2013) where the marketing of the IS network and the resource efficiency has led to the promotion of the regions. Regionally the benefits of IS networks can also extend to the sharing of skills and knowledge (Lombardi and Laybourn, 2012).

10 Reflections on Promoting the Transition to a Bio-based Economy

As can be seen in Paper II, biofuel production can collaborate with many other industries to share their by-products for added value. Many potential uses for by-products and their subsequent use for an abundance of products and processes have been identified, contradicting the typical linear view of biofuel production. This variety of products and uses for by-products outside the biofuel industry may allow for development of the industry more toward concepts such as biorefineries, where the systems deliver many valuable products. However, it is necessary not to overlook the abundance of by-products from external industries available for biofuel production.

Worldwide, the use of biomass has been promoted as a way to encourage sustainable economic growth and stimulate innovation in what can be termed the “bioeconomy” (Ekman, 2012). Much of the research concerned with the development of the bioeconomy is focused upon the use of advanced technologies for the production of bio-based products to add value to biomass products. By promoting the exchange of biomass and other organic wastes, the biofuel industry addresses this push toward the bioeconomy. According to Ekman (2012) and Gravitis (2004) concepts such as IS and industry clustering can provide innovative approaches to be used for further expansion of the bioeconomy in the EU by improving resource and energy efficiency. Furthermore, Ekman (2012) states that much of the research related to advanced biofuel production is focused on the technology development and the potentials of the biorefinery concept, though there is a need to focus on integration between firms and infrastructure sharing. This is especially important as many of the biorefinery concepts are hindered by high investment costs (Srirangan et al., 2012) while commercial biofuel technology has matured and is implemented worldwide on a large scale. By reviewing the systems that we have and optimizing them through synergies with external industries may allow the bioeconomy to expand alleviating introduction for the advanced biofuels.

In line with the development of a bioeconomy, Ristola and Mirata (2007) furthermore propose that moving toward large-scale, economy-of-scale based systems such as single actor biorefineries should be avoided. It has even been shown that such systems may lead to increased emissions from a systems perspective (Wetterlund, 2012). Additionally, further insight and assessment of impacts of such a “bio-based” economy are needed to take into account the possible increase in biomass use and how it affects other uses of the biomass (Kautto and Peck, 2012).

According to Ristola and Mirata (2007), IS could provide the background toward moving into new sustainable systems. A bio-based economy is therefore promoted as a more sustainable system where waste streams can be used for “smaller” systems, strengthening their success and potential for integration with other activities. Ristola and Mirata (2007) also suggest that distributing and making use of synergies regionally adds strength to the systems, as large scale industrial activities require large investments and infrastructure. Nonetheless, production in a distributed economy may be limited and does not allow for typical aspects of “growth” as measures of success, but more toward regional sustainability. As the development of energy consumption worldwide continues to grow, along with the use of resources, the distributed economy may promote regional sustainability. However, the distribution of resources is becoming increasingly concentrated regionally in e.g. cities, landfills and industrial areas. By taking advantage of these concentrations regionally can allow for material recycling and “closed loops” of energy and material flows regionally to promote the bio-economy (Lowe and Evans, 1995; Liwarska-Bizukojc et al., 2009). IS may be one way to initiate this, though it can be considered only part of the solution toward environmental sustainability.

11 Conclusions

Concepts from industrial symbiosis have been applied in the biofuel industry to offer insight into the integration between biofuel firms and external industries. This study highlights the diversity of possible exchanges between biofuel firms and external industries. The exchanges can be used to improve material recycling and add value to by-products and wastes. From the possible exchanges, it was found that numerous synergies may be possible between biofuel firms, though there is a large potential for synergies outside the biofuel industry, with e.g. the food, energy and chemical industries. Synergies with biogas producers were found to be most prevalent, especially those using external industry by-products for biomethane production. The results show that by-product synergies, i.e. exchanges of material, are more common than utility synergies although the later may offer more environmental performance benefits. As such, the biofuel industry and other identified external industries may use the results to identify possibilities for potential collaboration. However, it should be noted that many aspects and conditions must be addressed for the successful implementation of these synergies, including a convincing business case, licenses and available technology for the synergy.

As industrial symbiosis is assumed to provide benefits to firms in the IS network, a review of past attempts to quantify IS networks was conducted. Due to the lack of guidelines for such assessments, an approach was produced to quantify the environmental performance of IS networks, which highlights many of the critical factors for the assessments taking inspiration from life cycle assessment. These critical factors for the IS network quantifications include the functional unit, reference scenario selection, use of system expansion method versus physical allocation and choice of avoided conventional products and raw materials. The approach outlined provides a method for finding the environmental performance of an IS network compared to a reference scenario, in addition to a method for crediting firms for exchanged material and energy which can be useful for future quantifications of IS networks. It was found that this new approach may also have implications for taxes and subsidies, business relations and the communication of the environmental performance for firms in the IS network.

In this study the environmental performance of several scenarios based on an IS network in the biofuel industry have been assessed. From the results of this thesis there are reasons to argue that IS may lead to environmental performance improvements in the biofuel industry through by-product synergies, though the results depend upon the methodological choices used. These influential choices include the choice of a speculative reference scenario, allocation methods and choice of functional unit; which influence the results of the total system impacts and those applied to each firm of an IS network. The largest share of impacts for the IS networks studied in the appended papers were found to come from upstream impacts, e.g. the agricultural inputs for the biofuels. Furthermore, while the global emissions, e.g. greenhouse gas emissions, may be reduced, it is possible that local emissions may increase. It was also found that the scale of the exchanges and the energy systems used in the IS networks may have a large influence on the results. The results provide information for biofuel firms about the possible benefits of using by-products from other industries and how they may benefit from their own by-products. Furthermore, the representation of an IS network using renewable energy may be a welcomed addition the IS research community, which has many examples of fossil IS networks outside the forest industry.

The research offers inspiration for the use of industrial symbiosis to allow for the transition to a bio-based economy in a more sustainable approach, in contrast to the current promotion of large scale biorefinery concepts. By making use of by-products and other wastes regionally, and considering the diverse potential synergies between biofuel firms and external industries, IS may be used to produce renewable energy for more regional environmental sustainability.

12 Future Prospects for Reviewing Sustainability of IS

Based on the research provided in this thesis, a number of interesting questions may be asked about the applicability of the results in other areas. Europe, and other regions worldwide, have ethanol industries which could also use IS networks. It would therefore be interesting to understand what implications exchanges between, e.g. ethanol and biogas plants, in other areas of the world would have on the environmental performance. This is particularly interesting as Sweden, and in particular Händelö, has a unique position with a large share of renewable energy. By reviewing other systems in Europe with the approach provided would provide further insight into the implications of IS. Furthermore, the approach provided could be applied in different IS networks to provide insight to make it more robust.

As the thesis also provides many possible synergies between the biofuel and external industries, these could be explored further in a number of ways. In the discussion in preceding text, I provided a discussion on how IS could allow for a transition to the bioeconomy through, e.g. biorefineries. Synergies from this thesis could provide a background for such a study. The environmental performance of these synergies and the transition to biorefineries through IS networks could also be reviewed.

During the production of this thesis, I was also very interested in the true benefits of "material recycling" offered by IS and similar systems. Although environmental performance quantifications may be useful to address environmental impacts, they may fail to address other aspects of environmental sustainability. In the debate between commercial and advanced biofuels, typically greenhouse gas emissions or potential improvements are the primary focus. Additional indicators may be used to show the environmental sustainability of the system. For example, the degree of nutrient recycling in the system and even exergy analysis may offer further insight into the sustainability of the systems. As such, the use of IS could be compared with the large scale biorefinery concepts using these approaches to further grasp the effects from a systems perspective.

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"The dogmas of the quiet past are inadequate to the stormy present. The occasion is piled high with difficulty, and we must rise with the occasion. As our case is new, so we must think anew and act anew."

-Abraham Lincoln