

**LINKÖPING STUDIES IN SCIENCE AND TECHNOLOGY
THESIS NO. 1441**

**INDUSTRIAL SYMBIOSIS
FOR THE DEVELOPMENT OF
BIOFUEL PRODUCTION**

MICHAEL MARTIN

**Environmental Technology and Management
Department of Management and Engineering
Linköping University, SE-581 83 Linköping, Sweden**

COVER ART

The cover portrays the author's artistic view of industrial symbiosis. Many small to large firms and industries in the symbiotic activities are represented by circles. Linkages between these entities exist in various colors to represent the material and energy flows and their quantity. Interestingly, the circles and linkages are not all adjacent to one another and some can be seen as outliers, similar to those on the back cover. Furthermore, some of the exchanges do not take place directly between two firms, but use another firm to transfer the materials or even upgrade them for further use. Much like real world exchanges, this picture shows the relationship between firms under symbiotic activities from a holistic view, without boundaries and models.

LIU-TEK-LIC-2010:12

ISBN 978-91-7393-373-5

ISSN 0280-7971

Printed by: LiU-Tryck, Linköping 2010.

ABSTRACT

In recent years the popularity of biofuels has been transformed from a sustainable option for transportation to a questionable and criticized method. Many reports have therefore been produced to view biofuel production from a life cycle perspective; though results may be misleading. In a number of the reports, biofuel production is viewed in a linear manner, i.e. crops and energy in and biofuel out. However there is a large quantity of material and energy flows associated with biofuel production and these must be accounted for.

Industrial symbiosis concepts have therefore been applied in this thesis to the biofuel industry to identify possibilities to improve the material and energy flows. This has been done by mapping the exchanges and thereafter identifying possible synergies between biofuel firms and with external industries. Examples from regional biofuel synergies and exchanges with industrial partners have been highlighted. Many of the concepts have led to the identification of methods for increased integration and improvements, including the use of a renewable energy provider and the cooperation with external industries. Biofuels have therefore been found to profit from wastes, and instead of competition, benefit from one another, contrary to belief. This leads to an expanded market of raw materials for biofuel production.

Benefits do not only occur for the biofuel industry; from the application of biofuels, industrial symbiosis may gain further benefits. Several new concepts have been produced in this thesis to account for the unique material handling possibilities that biofuel production firms encompass. These include using biofuels as upcyclers of materials and the use of renewable energy as a way to improve environmental performance. Furthermore, a classification method has been produced to add more detail about individual exchanges for the industrial symbiosis literature in addition to viewing industrial symbiosis from an expanded system view to include exchanges beyond geographic proximity typical to the field.

ACKNOWLEDGEMENTS

The writing of this thesis has been a difficult yet exciting path to say the least. There have been plenty of distractions, frustration and obstacles along the way to overcome. However, in your hands you are holding the compilation of the first two years of my research. I am very proud of my results; results which could not have been possible without the help of many others.

To begin, I would like to thank Mats Eklund for his vision, guidance and support in the project. Thereafter, my colleagues at the Division of Environmental Technology and Management deserve gratitude for their help, insight and most importantly coffee breaks where one can escape the lonely world of researching.

The research project could not have been possible without the help and support of many regional biofuel actors. Our *Biofuel Reference Group* deserves immense gratitude. I would like to thank our contacts at Tekniska Verken, Svensk Biogas, Agroetanol and Ageratec for their cooperation and invaluable information for this research project. Furthermore, I am grateful for those funding the project, FORMAS and the biofuel reference group, for whom I hope that conclusions from this research will end up being implemented.

I would also like to thank Sofia Lingegård for her support. Thank you for listening and consoling me during times of frustration in both my work and life. Finally, I am very happy about the new member of our family, our new dog, a Hungarian Vizsla, Nívós for which I have gained an immense drive to finish writing this thesis.

LIST OF APPENDED ARTICLES

Article I- Improving the Environmental Performance of Biofuels with Industrial Symbiosis
(Submitted to *Biomass and Bioenergy Journal*)

Article II- An Inventory and Analysis of Synergies in the Biofuel Industry (Submitted to
Bioresource Technology)

Article III- Classification of Industrial Symbiosis Synergies: Application in the Biofuels
Industry (Submitted and Revised for the *Journal of Industrial Ecology*)

My Contribution to Articles

Article I- Major contribution; both data collection and writing.

Article II- Major contribution; data collection, writing, etc.

Article III- Major contribution; writing and shared contribution for data collection.

Related Publications

Martin, M., & Fonseca, J. (2010). 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.*

TABLE OF CONTENTS

1	INTRODUCTION.....	1
1.1	Aim.....	2
1.2	Definitions.....	3
2	SYSTEM BOUNDARIES AND LIMITATIONS.....	5
2.1	Biofuel Production Systems and System Boundaries.....	5
2.2	Industrial Symbiosis Limitations.....	6
3	BIOFUELS.....	7
3.1	Biodiesel.....	7
3.2	Biogas.....	9
3.3	Ethanol.....	11
3.4	Biofuel Production in Retrospect.....	12
4	INDUSTRIAL SYMBIOSIS.....	13
4.1	Industrial Symbiosis as a Branch of Industrial Ecology.....	13
4.2	By-Product and Utility Exchanges.....	14
4.3	Co-Location and Geographical Proximity.....	14
4.4	Energy Systems for Eco-Industrial Parks.....	15
4.5	Industrial Symbiosis Taxonomy in this Work.....	15
4.6	Industrial Symbiosis in Retrospect.....	17
5	METHODOLOGY.....	19
5.1	Research Process and Strategy Identification.....	19
5.2	Biofuel and Industrial Symbiosis Literature.....	20
5.3	Interviews and Focus Group Interviews.....	21
5.4	Field Visits.....	21
5.5	Using a Case Study.....	22
5.5.1	Selection of Cases: Symbiosis Activities of Östergötland.....	23
5.5.2	Data Collection and Analysis.....	24
5.5.3	Shaping Theories and Enfolding Literature.....	24
5.6	Contribution of Appended Articles and Methods Employed.....	25
6	RESULTS.....	27
6.1	Händelö as an Example of Industrial Symbiosis Applied in the Biofuel Industry.....	27
6.2	Linköping: Symbiotic Activities for Biogas Production.....	29
6.3	Inventory of Synergies and Characteristic Exchanges and Industries.....	30
6.3.1	Integrating the Biofuel Industry.....	31
6.3.2	Biofuel Industry Integration with External Industries.....	31
6.3.3	By-Product vs. Utility Synergies.....	33
6.4	Classification of Individual Synergies.....	34
7	HOW CAN THE BIOFUEL INDUSTRY BENEFIT FROM CONCEPTS OF INDUSTRIAL SYMBIOSIS?.....	37
7.1	More Effective Material and Energy Flows.....	37
7.2	New Raw Materials and Markets for By-Products and Utilities.....	38
7.3	The Anchor Tenant as a Supplier of Renewable Energy.....	39
7.4	Expanding System Boundaries to Improve Environmental Performance and Energy Efficiency.....	39
7.5	Material and Energy Cascading.....	40
8	HOW CAN INDUSTRIAL SYMBIOSIS BENEFIT FROM THE APPLICATION OF BIOFUELS?.....	41
8.1	Biofuels as Upcycling Tenants.....	41
8.2	Geographic perspective.....	42
8.3	Additional Details for Individual Exchanges.....	42
8.4	Products as Synergies.....	43

8.5 Using Renewable Energy for Industrial Symbiosis	43
9 CONCLUSIONS	45
9.1 Biofuels Benefiting from the Field of Industrial Symbiosis and Relevant Concepts	45
9.2 Benefits to the Field of Industrial Symbiosis Using the Application of Biofuels.....	46
9.3 Further Research	47

LIST OF FIGURES

Figure 1: System Boundaries applied to the Life Cycle of Ethanol Production.	5
Figure 2: Biodiesel Material and Energy Flow Analysis	7
Figure 3: Biogas Material and Energy Flow Analysis	9
Figure 4: Ethanol Production Material and Energy Flow Analysis	11
Figure 5: The Three Levels of Industrial Ecology (Chertow, 2000).....	13
Figure 6: Taxonomy/Hierarchy of terms used in this thesis	16
Figure 7: Linköping Biogas Production and Synergies	29
Figure 8: Classification Tool for Biofuel Synergies	35

LIST OF TABLES

Table 1: Process of Building Theory from Case Study Research	23
Table 2: Contribution and Methods used in Appended Articles	26
Table 3: Selected Synergies between Biofuel and External industries	30
Table 4: Biofuel and External Industry Synergistic Possibilities.....	32
Table 5: Interaction with Biofuel and External Industries	32
Table 6: By-product vs. Utility Synergies.....	33
Table 7: Classification/Taxonomy in Industrial Ecology and Industrial Symbiosis.....	34

THESIS OUTLINE

Chapter 1 provides a broad introduction to the background of the thesis to describe the use of biofuels for transport, criticism and possible use of industrial symbiosis to improve many of these critical arguments. The aims of the thesis as well as several important definitions needed throughout the thesis are also presented.

Chapter 2 addresses the limitations on the biofuel and industrial symbiosis concepts applied in this thesis and includes a representation of the system boundaries for the entire biofuel production life cycle.

Chapter 3 affords the reader with a brief review of the production methods, reactions and material and energy flows for the production of biodiesel, ethanol and biogas. The chapter also describes more detail into some of the criticism and suggests that system integration and a wider systems perspective could alleviate criticism related to the energy efficiency, competition, etc.

Chapter 4 provides a theoretical background into the concepts of industrial symbiosis. The material presented is related to that employed in the thesis. Moreover, a taxonomy/hierarchy is provided to delineate how the terms are used in the text for further clarification.

Chapter 5 addresses the methodology used in this thesis and the appended articles. A review of the data collection methods, case study and overall research process has been outlined in the chapter.

Chapter 6 presents the results of appended articles that are applied to the aims of the thesis.

Chapter 7 examines how biofuels make use of concepts from industrial symbiosis and how these can provide benefits to expand the use of integration for material and energy exchanges between biofuel and other external industries.

Chapter 8 thereafter contradicts Chapter 7 by showing how industrial symbiosis can benefit from the application of biofuels. New concepts and utilization of existing concepts in the industrial symbiosis field have been provided.

Chapter 9 concludes the thesis with a retrospective view of the results obtained and reviews the mutual benefits biofuels and industrial symbiosis can pose. Furthermore, a description of interesting question and future research that could come from this work is provided.

1 INTRODUCTION

As the world continues to develop our obligation to develop in a sustainable manner to allow for the preservation of nature and resources for future generations has become increasingly important. In order to alleviate our impact on the environment, renewable resources and the sustainable consumption of resources have become important drivers worldwide.

The adaption of renewable energy has become a goal in many countries worldwide, though the motives may vary. In many countries renewable energy is supported to reduce imports of fossil fuels and become more self sufficient while in others the reduction of emissions is the primary driving force. Biofuels, especially in developing countries, have been identified as a promising medium toward development to reduce imports and emissions, increase profits and provide employment in rural areas. Nevertheless, especially in the case of biofuels, what started as means for sustainable development has now shifted to a debate.

Biofuels for transportation exist in nearly every country worldwide. These fuels can be employed in current infrastructure and even blended with fossil fuels to reduce emissions and provide regionally produced energy. However, what can be concluded about the current production of biofuels worldwide? Many arguments have been brought forward, ranging from biofuels being a threat to humanity to biofuels being an answer to the worlds growing concern over oil supplies. What is certain however is that there are many critical discussions about the production and use of biofuels for energy in the scientific literature due to a number of factors. A large number of life cycle analyses have been produced in recent years with a wide range of results. Biofuels have been shown to be a good alternative in several cases, while in many others the life cycle emission and impacts have resulted in similar values to fossil fuels. These reports should be meticulously reviewed however as the assumptions and systems boundaries used may lead to misleading information (Börjesson, 2009; Gnansounou et al., 2009; Taheripour et al., 2010).

Supplementary to this, the energy efficiency of biofuel production is often shown as being very unsatisfactory. This is especially true for some fossil based ethanol production plants in the USA, to which many research results are based (Börjesson, 2004). Not all biofuel plants are fueled with fossil energy. Integration with other industries and the employment of bioenergy for process heat and energy could dramatically improve the energy efficiency of biofuel production (Börjesson, 2009).

One diversion used in the current discussion of biofuels, is the argument that future technologies, including Fischer-Tropsch fuels, thermal gasification, cellulosic ethanol production and many more techniques will solve problems for the production of current biofuel production methods. Future technologies will require the current use of biofuels to alleviate some of the current issues and problems with infrastructure, vehicles and legislation (c.f. Hughes, 1987; Hughes, 1993). Biofuel production systems currently in place worldwide will thus need to be optimized to reduce environmental impacts and improve the energy balance. One method of doing as such is to integrate systems by using the concepts of industrial symbiosis.

Concepts from the field of industrial symbiosis (IS) can offer biofuels many interesting routes to improve the environmental performance and integrate with other industries. The aim of

industrial symbiosis is to engage traditionally separate industries in a collective approach to create competitive advantages through exchanges and synergistic possibilities (Chertow, 2000). Biofuel production processes worldwide currently contain a wide range of material and energy inputs outputs. By using the concepts of industrial symbiosis, these flows of material and energy can be optimized to increase environmental performance and create more sustainable products.

1.1 Aim

The overall aim of this thesis is to provide for the improvement of the biofuel production industry through the use of concepts from industrial symbiosis. This will be done by outlining the input and output of material and energy for biofuel production processes and thereafter finding possible approaches to make processes more efficient through integration. These integrations with other industries and processes are done with the ambition of improving the environmental performance. Industrial symbiosis will not only provide improvements for the biofuel industry. Results from this thesis are aimed at providing innovative details and approaches in the area of industrial symbiosis by using biofuels as an application to find new approaches for synergistic possibilities.

Important research questions to be answered in this thesis are as follows:

- What can industrial symbiosis offer for the biofuel industry for possible approaches for interaction which could result in improvements of efficiency and environmental performance?
- How can the biofuel industry provide improvements and concepts for industrial symbiosis

Sub-questions also highlighted in the thesis primarily through the appended articles are as follows:

- How can IS theoretically improve the environmental performance and energy efficiency of biofuels? What theories from IS will allow for synergies and environmental improvements?
- What types of synergies are possible in the biofuel industry? What other industries can collaborate with biofuel industries? How can biofuel industries, i.e. biogas, bioethanol and biodiesel production, be integrated?
- What further classification of synergies is needed in the field of industrial symbiosis? How can further details into individual synergies offer benefits to the field?

1.2 Definitions

The intention of this thesis is to develop upon approaches to improve the biofuel industry through the concepts of industrial symbiosis with an underlying goal to improve the environmental performance. The terms used in this thesis are thus entirely related to the environment and processes of biofuel production, strictly speaking from an environmental and engineering point of view.

Biofuels, for the remainder of this thesis, will be defined as fuels 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 primarily biogas, biodiesel and bioethanol¹, however other biofuels for transportation exist, e.g. methanol, dimethyl ether (DME), propanol and butanol but are not used in this work (International Energy Agency, 2005; Worldwatch Institute, 2006).

Throughout this thesis the term *biofuel industry* will be used to convey the biofuel production industries, i.e. the biogas production, biodiesel production and ethanol production plants. It may be argued that the plants producing the respective biofuels could simply be called plants. However, as biofuels will be exemplified in aggregate so too will the production industries involved.

The term *synergy* is used in the entirety of this work as material and energy exchanges between industries, companies, production facilities, individual firms, etc. Synergies will not be used to describe business and economic cooperation between companies. Different categories of synergies will be used in the text, namely by-product synergies and utility synergies.

An expression often referred to in the text is the *environmental performance* of the biofuel industry. Environmental performance is henceforth related to the emissions and impact processes have on the environment.

Efficiency is used in several contexts in this thesis. Efficiency when mentioned with regards to energy is concerned with the optimization of energy input-output ratios. Moreover, efficiency can also be defined as improving a product by using the least amount of materials as possible.

Integration in this thesis is used primarily to denote the incorporation of processes and material exchanges on a macro level. These exchanges and shared processes can be between industries, the municipality and internally in the individual processes.

Further information and definitions associated with industrial symbiosis and industrial ecology concepts are also included in the corresponding chapter.

¹ The term ethanol is typically interchanged with bioethanol and will therefore be done so in the remainder of this text.

2 SYSTEM BOUNDARIES AND LIMITATIONS

The focus of this thesis is principally concerned with the adoption of concepts from industrial symbiosis for the biofuel industry. Correspondingly, the scope of this thesis will apply to the areas encompassed by the two fields. The subsequent sections describe the limitations placed on the two fields as applied in this work.

2.1 Biofuel Production Systems and System Boundaries

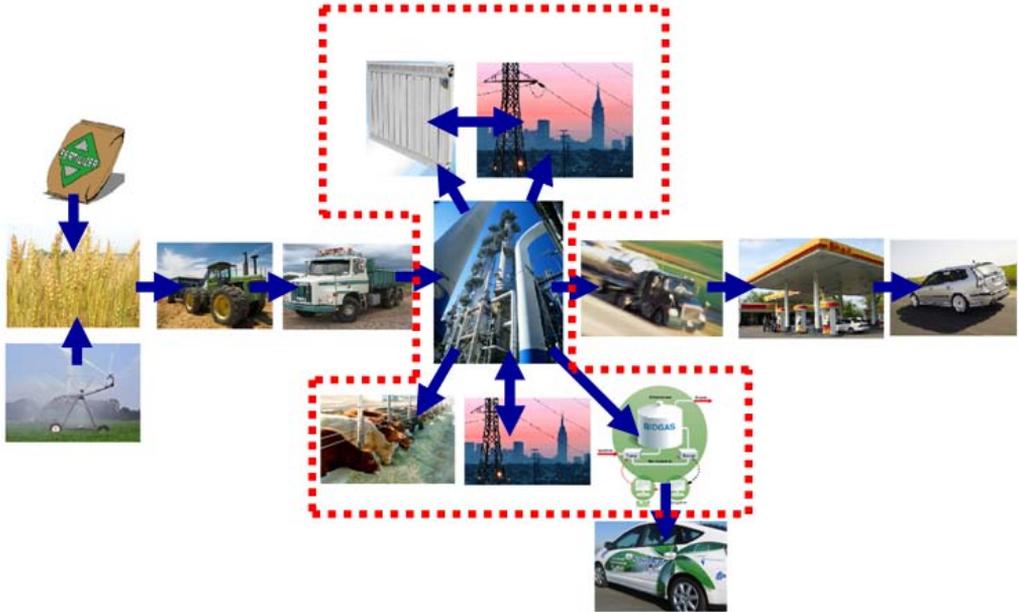


Figure 1: System Boundaries applied to the Life Cycle of Ethanol Production.

Note that the red dashed line is primarily concerned with the energy and material flows into the production process.

As previously mentioned, the criticism related to biofuels is done so on a wide range of issues. This is especially true in the current debate about agricultural issues, food vs. fuel and the emissions from vehicles. Comments therefore range throughout the whole life cycle of biofuel production though certain aspects of the life cycle have more repercussions than others.

Agricultural aspects, the production process and the use of biofuels for transport produce the largest impacts in the life cycle of biofuel production and use (Bernesson et al., 2004; Börjesson & Tufvesson, 2010). As the aim of this thesis is to better the biofuel production, naturally the agricultural and production processes would be viewed. Nonetheless, the focus of this thesis will be limited to the production aspects. This is due to the fact that industrial symbiosis typically is contained within an interfirm approach, primarily the material and energy flows of the production processes (Chertow, 2000). It may be argued that interfirm interactions may take place throughout the whole life cycle of biofuel production and include the agricultural and delivery systems, however the primary focus will be placed upon those

flows of material and energy to the biofuel production firms. In the text synergies with external industries are in many cases considered. Some of these synergies even take place between production outputs and the disregarded aspects of the life cycle of biofuels, i.e. the agricultural and use phase. These synergies nonetheless have a direct link to the production processes and do not include expanded systemic aspects into the external industries. Focus will therefore be largely placed on the “benefits” for the production process.

2.2 Industrial Symbiosis Limitations

Industrial symbiosis concepts can take on two approaches to explain the integration of industries and actors, namely those related to *engineering aspects* (technology, integration and material exchanges) and those related to the *social context*. The activities of material and energy exchanges as seen by Boons and Baas (2007) do not simply occur in a vacuum. Instead they are shaped by the social contexts in which they occur. Social contexts are sometimes referred to as the embeddedness of the system and can include the cognitive, structural, cultural, political, special and temporal embeddedness (L. W. Baas & Huisingsh, 2008). Notwithstanding the social context of industrial symbiosis is not applied in this thesis. The thesis is primarily focused upon the engineering aspects of the synergies between industries in the production of biofuels, i.e. the by-product and utility synergies. Therefore, the dissemination of industrial symbiosis, reasons for implementation, legislation, agreements, reasons for, reverse salients and many other issues related to the social aspects and contexts of industrial symbiosis will not be explored in this thesis.

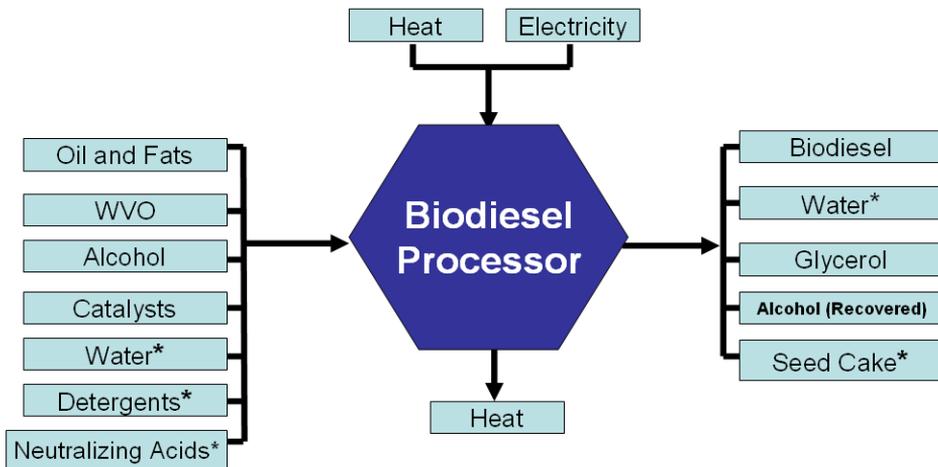
Often in the production of biofuels, by-products and raw material are consumed and taken from outside of the regional economic community. Raw materials, such as vegetable oil for biodiesel production, are sold on international markets and are transported large distances. This is one criticism biofuel production has received. However, by-products and other raw materials can originate regionally, though economic feasibility often comes into play. In order to allow for the use of many of the utility and by-product synergies between biofuel and external industries, the geographical proximity of industries, firms, etc. for industrial symbiosis will not be considered in this research project (Chertow, 2000; Gibbs & Deutz, 2007). Although a number of the synergies originate or can be consumed in the regional perspective, it is assumed that synergies can take place beyond these borders; the proximity for being called “industrial symbiosis” or an eco-industrial park will not be discussed.

3 BIOFUELS

Biofuels are not simply *biofuels*. Each biofuel is unique and has different applications. Additionally, for each biofuel there are many different production techniques. The most common of these include the fermentation of sugar to produce alcohol, transesterification of fats and oil to make biodiesel and the anaerobic digestion of organic material to produce biogas. While each biofuel is unique and has different applications many argue that there is an underlying competition between them. One question typically arises when dealing with the production and choice of biofuels for transport; which is better? Competition includes the market for their use, production techniques and the comparisons of environmental performance and energy efficiency (Börjesson & Mattiasson, 2008; de Wit et al., 2010; Murphy & Power, 2008; Power & Murphy, 2009). Biofuels should not simply be seen as competing. Just as suggested, there are unique applications and material and energy inputs and outputs respective to each biofuel. These flows can even be used to produce more biofuels from a limited input of materials. By mapping the material and energy flows, biofuel production firms can even cooperate amongst themselves and with external industries.

The following sections will outline the material and energy flows of three biofuels as well as provide a short description of how each biofuel is produced; i.e. for biodiesel, biogas and bioethanol. This will be used in later sections to apply concepts of industrial symbiosis in the biofuel industry.

3.1 Biodiesel



* In some processes

Figure 2: Biodiesel Material and Energy Flow Analysis

General Description and Reaction

Biodiesel is a fuel similar to its diesel counterpart used as a transport fuel in both unblended and blended forms. Biodiesel is produced through the transesterification of fats and oils into fatty acid alkyl esters. The transesterification reaction consumes oil and alcohol to produce the main product biodiesel and a by-product, glycerol. The resulting hydrocarbon chain contains an alcohol group attached and is comparable in length to petroleum based diesel, i.e. $C_{10}H_{22}$ - $C_{15}H_{32}$ (Mittelbach & Remschmidt, 2004; Worldwatch Institute, 2006).

Inputs

The major inputs for biodiesel production include fats and oils and alcohol. The alcohol used is typically methanol. Some of the oil and fats used to produce biodiesel worldwide include:

Vegetable Oil

- Sunflower Oil
- Rapeseed Oil
- Jatropha Oil
- Palm Oil
- Coconut Oil
- Cottonseed Oil
- Soy Oil

Fats and Wastes

- Waste Vegetable Oil (WVO)
- Used Cooking Oil (UCO)
- Beef Tallow
- Pork Lard
- Poultry Fat
- Fish Oil

Supplementary to the major material flows needed for the transesterification reaction, a number of additional material and energy are required. In many cases a catalyst, and sometimes acid, is used to speed up the reaction and ensure a good reactivity. Excess alcohol is also usually provided in order to ensure that all glycerol molecules are exchanged.

The production process requires some energy inputs. These include the use of electricity for various pumps, heaters and electronic controls. Heat can also be provided by an external heating source such as industry steam, coal, solar power or another fuel source. Temperatures delivered for the process are usually around 60°C (Demirbas, 2009; Martin et al., 2009; Mittelbach & Remschmidt, 2004; Predojević, 2008; Worldwatch Institute, 2006).

Outputs

Subsequent to biodiesel production, a number of outputs are produced. These include firstly the biodiesel and thereafter by-products, including glycerol, waste water (if water washing is used) and excess alcohol. The excess alcohol, usually methanol, can be recovered using various techniques. Seed cake may in some cases also be a by-product of the biodiesel production process, when the producer not only uses the oil but also presses the seeds. Processing temperatures are rarely over 60°C, however excess heat is cooled in many processes and could be used for additional processes (International Energy Agency, 2005; Martin et al., 2009; Mittelbach & Remschmidt, 2004; Worldwatch Institute, 2006).

3.2 Biogas

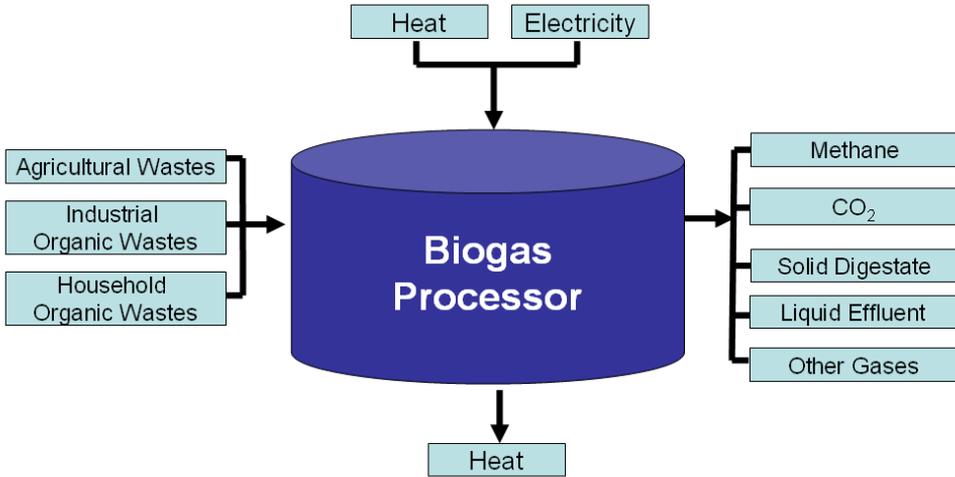


Figure 3: Biogas Material and Energy Flow Analysis

General Description and Reaction

Biogas², or biomethane, is a gaseous fuel produced through the anaerobic digestion of organic material. Anaerobic digestion is carried out in several different phases. First organic material is broken down by hydrolytic bacteria and transformed into fatty acids. These fatty acids are then decomposed into acetic acid by acetogenic bacteria. Finally methanogenic bacteria produce *raw gas* from the resulting acetic acid, which will then be upgraded into biogas. This raw gas contains roughly 60 percent methane, 30 percent carbon dioxide and 10 percent additional gases, including hydrogen sulfide, hydrogen, nitrogen, ammonia and carbon monoxide. Upgrading is carried out by many techniques to literally “clean” the gas and extract the final product, biogas, which contains around 98% methane (Linköpings kommun, 2008; Neves et al., 2006; Svensk Biogas AB, 2009).

Inputs

The organic material used for anaerobic fermentation can come from a literal “smörgåsbord” of inputs, although typical materials include agricultural, industrial and household wastes (Linköpings kommun, 2008; Svensk Biogas AB, 2009). In Sweden, typical raw materials for biogas production include:

² The term biogas is typically used to denote upgraded version of the *raw gas* produced in the anaerobic reaction.

- Manure
- Food Residues
- Biomass
- Sewage
- Glycerol
- Fats
- Sludge
- Alcohol
- Dairy by-products
- Municipal wastes
- Fruit residues

The production of biogas must be conducted under optimal and controlled conditions. Heating is therefore used in many cases to keep the substrate at optimal conditions for the bacteria to produce biogas. Electricity and heat are therefore used during the process; electricity for mixing and heat for optimizing the temperature.

Outputs

While the production of biogas is the primary goal, other important by-products are simultaneously created. Solid digestate and liquid digestate are the bulk of the material produced. These have applications as bio-fertilizers or substrates for bioenergy product, i.e. use in CHP plants. The other gases produced during anaerobic digestion which are contained and thereafter removed during the upgrading process, could also be used. Carbon dioxide, hydrogen, hydrogen sulfide and other gases removed can be stored for subsequent use by a number of technological solutions (Lantz et al., 2007; Svensk Biogas AB, 2009). Excess heat is rarely made use of or upgraded as biogas production takes place around 38°C.

3.3 Ethanol

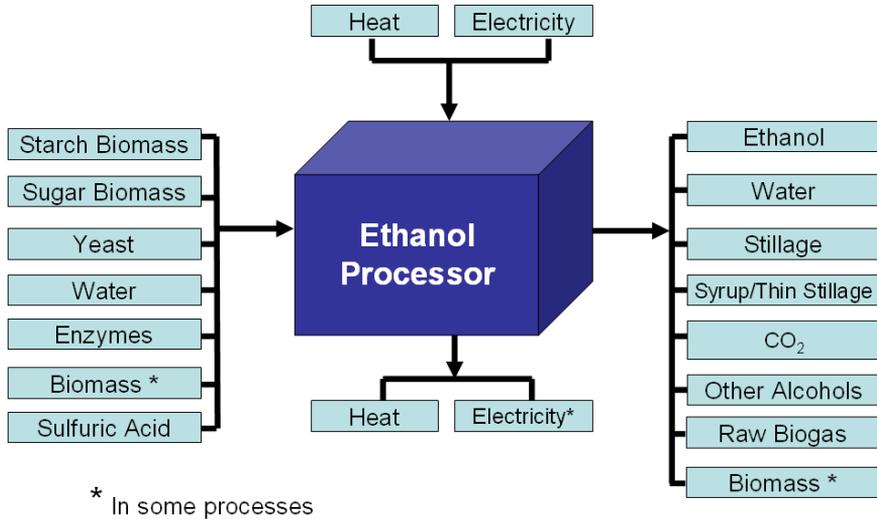


Figure 4: Ethanol Production Material and Energy Flow Analysis

General Description and Reaction

Bioethanol is the product of the fermentation of simple sugars. The simple sugars, i.e. glucose, can be derived from either starch or sugar based crops. If starch based crops are used, they must undergo the process of saccharification in order to convert the starch into simple sugars. Sugar based crops are easier to produce as the sugars must simply be broken apart before fermentation. Water and yeast is mixed with the sugar and fermentation thereafter begins. The fermentation produces alcohol, in this case ethanol, carbon dioxide and stillage. The mixture now contains ethanol. In order to remove the ethanol, the mixture must be distilled. In this process, ethanol is removed from the water and stillage mixture. Thereafter the stillage is used for many other purposes and the ethanol is dehydrated to a very high percentage alcohol content, depending on the application and specification of the customer (International Energy Agency, 2005; Lantmännen Agroetanol AB, 2009a; Worldwatch Institute, 2006).

Inputs

In the process of ethanol production many inputs are required. Those inputs include yeast for fermentation, sugar or starch based crops, process water, optimizing chemicals (such as sulfuric acid to balance the pH) and enzymes to undergo saccharification. Some of the crops used for the production of ethanol include:

Starch Based

- Wheat
- Barley
- Cassava
- Corn (Maize)

Sugar Based

- Sugarcane
- Sugar Beets
- Sweet Sorghum

Fermentation of crops is carried out around 100°C. Energy is thus required to heat up the process, which is usually delivered by steam or some other boiler unit. Biomass from the crops, whether straw from cereal based ethanol production or bagasse from sugar based crops, can be used for energy inputs. In several processes worldwide the excess biomass is combusted to run a co-located combined heat and power plant (CHP). Electricity is used in the many pumps and monitoring equipment throughout an ethanol plant.

Outputs

Apart from the many inputs needed for the fermentation of sugar and starch crops to produce ethanol, many outputs are also generated. These include waste water, stillage, syrup, thin stillage, carbon dioxide and other alcohols (Bai et al., 2008; International Energy Agency, 2005; Murphy & Power, 2008; Worldwatch Institute, 2006).

Stillage and thin stillage are products of the ethanol production process. However, the dry matter (DM) content of each is different; stillage having around 90% DM and thin stillage, also called syrup, with around 30% DM. Stillage is also known as DDGS (distillers dried grain solubles). Waste water is generated from the separation of ethanol from the stillage and when reducing the water content of the stillage (Kim et al., 2008; Lantmännen Agroetanol AB, 2009a; Lantmännen Agroetanol AB, 2009b).

In the fermentation process, alcohols other than ethanol are also produced, e.g. fusil oil. These can be separated only in the later stages of the distillation and dehydration phases (Martin et al., 2009). Carbon dioxide is also a major product of the fermentation process. For every unit of crop input, around one third is transformed into carbon dioxide (Lantmännen Agroetanol AB, 2009a).

3.4 Biofuel Production in Retrospect

A large number of reports have been produced in recent years on the subject of biofuels. As mentioned previously, the question of which biofuel is best is a common theme. Likewise, there are many comparisons of the environmental impacts from the production of biofuels. Results from these reports encompass a wide range of results which conclude with biofuels being an excellent alternative to fossil fuels and reports which conclude that biofuels produce more emissions and impacts than fossil fuels. However, these reports should be reviewed in their entirety as they take into account varying system boundaries and assumptions, leading to a large range in figures concerning their environmental performance (Börjesson, 2009; Gnansounou et al., 2009).

As shown in the preceding sections, the production of biofuels includes many material and energy inputs and outputs. Many of the aforementioned critical reports include only a limited number of the material and energy flows for the biofuel production process and subsequent life cycle assessments. Seeing that each respective biofuel is not the sole output of the production process, the entire production process should be viewed, including all inputs of material and energy. By not taking into account many of the important products of biofuel production, i.e. by-products and energy, many of the estimates can be misleading (Taheripour et al., 2010).

4 INDUSTRIAL SYMBIOSIS

Industrial symbiosis can be defined as a concept aimed at engaging traditionally separate industries in a collective approach to create competitive advantages through resource exchanges, synergistic possibilities and cooperative approaches based on their geographic proximity (Chertow, 2000). An important notion of industrial symbiosis is that the individual firm is not seen as an island, but is involved interactively with other firms to promote mutually beneficial exchanges, i.e. “win-win” situations.”

4.1 Industrial Symbiosis as a Branch of Industrial Ecology

Industrial ecology is a concept based around the principal of minimizing wastes and making the flows of material and energy more circular through the use, and reuse, of wastes for new products. This can be accomplished in many ways, e.g. through material and energy cascading and recycling, for which many processes make reference to the ecosystems as an integral association. Ecosystems thus provide the most promising example of sustainable systems to be mimicked by industry (Frosch & Gallopoulos, 1989; Lowe, 2001). Industrial ecology can be described as a broad holistic framework consisting of tools, principles and perspectives borrowed and adapted from ecology for the analysis of industrial systems (Lowe & Evans, 1995; Lowenthal & Kastenberg, 1998). Much like ecological systems, the concept of industrial ecology can function and be applied for optimization of industrial activities on many levels. In particular, three levels, i.e. the global, interfirm and individual facility level have been described for industrial ecology.

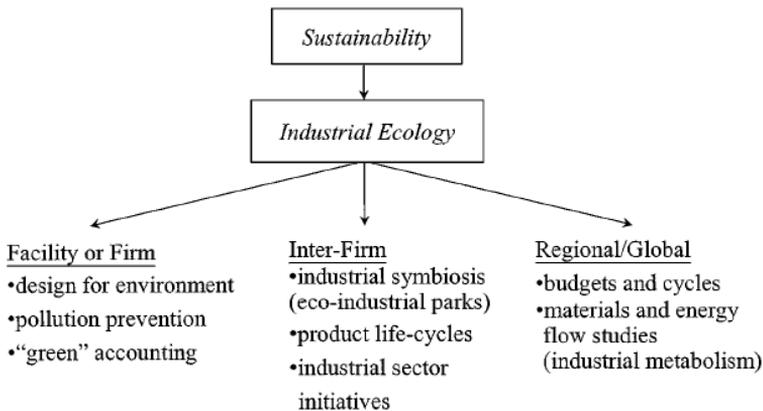


Figure 5: The Three Levels of Industrial Ecology (Chertow, 2000)

Industrial symbiosis (IS) is a branch of industrial ecology with a focus upon the interfirm level (Chertow, 2000; Jacobsen, 2006). Firms and industries are therefore involved in symbiotic networks of exchanges. These symbiotic networks of firms are often referred to as eco-industrial parks, (Lifset & Graedel, 2002) an application of industrial symbiosis. The branch of industrial symbiosis provides many relevant contributions to IE. It does so by adopting and implementing ecosystem traits to promote sustainable resource use at the interfirm level. IS allows for further studies on the characteristics of the exchanges, drivers for their success and the development of cooperation between firms and industries. (Ehrenfeld, 2000; Chertow 2000).

4.2 By-Product and Utility Exchanges

Physical resource exchanges between firms are a primary concern of industrial symbiosis. These exchanges allow for the collaboration of the firms to handle wastes, raw materials, energy and by-products. Exchanges have many different forms, though they can be classified as several unique types.

The Center of Excellence in Cleaner Production of Curtin University (CECP) (2007) and van Beers et al. (2007) have argued that a distinction of the types of exchanges between firms is needed. Accordingly, they have classified exchanges between industries as by-product synergies, utility synergies and supply synergies. Supply synergies involve the co-location of firms with their key customers; as mentioned in the scope this will not be handled in this research project.

By-product synergies are synergies which involve the use of previously disposed by-products created from process 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, i.e. water, infrastructure and energy. These synergies typically include the sharing of energy, water, electricity, heat, joint treatment of emissions as well as recovery and treatment plants. Whereas biofuels may be classified as energy carriers, they will not be classified as utilities, and will therefore be regarded as products. The biofuels can therefore be regarded as either physical synergies or by-product synergies.

4.3 Co-Location and Geographical Proximity

Co-location and the geographical proximity firms is often considered the key condition for industrial symbiosis (Jacobsen, 2006). This is often anticipated to reduce transport distances, costs and environmental impacts. However, geographical proximity may not be advantageous in some industries, as may be illustrated in the bioenergy industry. Chertow (2000) enumerates this by examining the exchanges between firms in a so called *virtual exchange*. These exchanges take place between firms in a broad region, which allows for further integration within a regional economic community. This increases the potential for the identification of by-product exchanges by allowing for an expanded number of firms to be part of industrial symbiosis. Pipelines can even be used to transport material and utilities to non-neighboring facilities to make use of synergies (ibid.). Christensen and Kjaer (2009) likewise assert that by aiming for co-location many potential linkages between firms may be overlooked and in the bioenergy field, these limitations should be expanded to further include partners outside those co-located.

4.4 Energy Systems for Eco-Industrial Parks

In industrial symbiosis an anchor tenant typically acts as a way to develop eco-industrial parks and physical resource exchanges. Firms are attracted to an eco-industrial park to make use of the abundance of material and energy exchanges from anchor tenants, and thereafter develop alongside the anchor tenant to realize mutual benefits (Lowe, 1997). The realization of synergies, especially utility synergies, is complex for some industries. In order to put into practice many potential synergies, anchor tenants are employed to handle infrastructural concerns. Co-location can allow firms to optimize their energy usage and therefore improve products and environmental performance (Danestig et al., 2007; Ljunggren Söderman, 2003)

The most common form of anchor tenants in industrial symbiosis literature are the energy systems. Anchor tenants typically take the form of waste incineration plants, combined heat and power plants or refineries (Burström & Korhonen, 2001; Chertow, 2000). These firms offer excellent possibilities due to their available heat, steam and electricity production as well as a means by which to dispose of wastes, e.g. biomass. Nonetheless, common to most industrial symbiosis developments are the use of fossil based systems. This is true even for the inspirational case of Kalundborg in Denmark which contains a coal plant as an anchor tenant (Chertow, 2000; Jacobsen, 2006).

4.5 Industrial Symbiosis Taxonomy in this Work

Classification of industrial symbiosis has been difficult to accomplish, due to the fact that many of the terms used to describe concepts of industrial symbiosis are confused and have varied meaning between disciplines (CECP, 2007; Jacobsen, 2006). As an example Jacobsen (2006) describes how industrial symbiosis concepts can be expressed with terms such as eco-industrial parks, industrial ecosystems, islands of sustainability, by-product exchange, etc.

Despite the numerous terms involved in the field of industrial symbiosis, an arrangement can be made to provide a clear overview of how these terms relate to one another. Shown in the figure below and defined in the subsequent text is a hierarchical overview of the terms used in this thesis and how they are represented and associated to one another. Frequently the *concepts* will be referred to, which include everything under the industrial symbiosis in the hierarchy shown below.

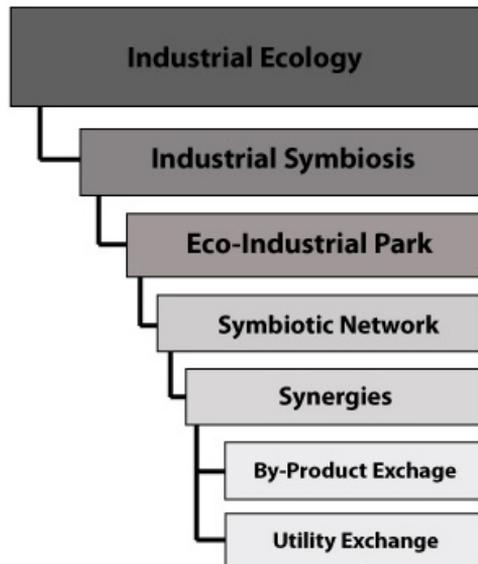


Figure 6: Taxonomy/Hierarchy of terms used in this thesis

- **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**- can be categorized as a field of research focused on collective resource optimization based on by-product exchanges and utility sharing that biological symbiosis mimics (Jacobsen, 2006).
- **Eco-industrial parks**- places/limited regions where the concepts of industrial symbiosis are put to work to bring about symbiotic networks of firms. These are the concrete realizations of industrial symbiosis concepts (Chertow, 2000).
- **Symbiotic networks**- A collection of firms gathered to exchange 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 a symbiotic network.
- **By-product exchanges**- 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).

4.6 Industrial Symbiosis in Retrospect

Inasmuch as industrial symbiosis concepts may be confusing, they are an application of the wider framework of industrial ecology. The aforementioned taxonomy shows only a handful of the many terms used to describe industrial symbiosis which will be used in this text.

In this research project, the term industrial symbiosis will not only be limited to and require geographical proximity. Synergies between industries will be applied regardless of the geographic proximity unless explicitly stated. Furthermore, the application of biofuels will be further studied as they may offer many possibilities for the industrial symbiosis field.

5 METHODOLOGY

As the proceeding text will enumerate, a variety of methods have been used to conduct the research project. The compilation of these methods has been used to produce the results of the later sections of this thesis. Methods include literature reviews, a case study, field visits and interviews with experts in the biofuel field. Included in this text is also a superficial review of the methods used in the appended articles.

To establish the grounds for the research project and provide a candid account of how the events unfolded in this research project the section entitled, *Research Process and Strategy Identification* will present the overall project method.

5.1 Research Process and Strategy Identification

This research project was founded on the idea that biofuels could be “bettered,” explicitly seeing biofuels not as either good or bad, but how much better they could be. Under the research project entitled “*Synergies for Improved Environmental Performance of 1st Generation Biofuels for Transportation*,” biofuel production was further studied to find how industrial symbiosis concepts could benefit the biofuel production industry and quantify how synergistic activities will improve the energy and environmental performance of biofuels for transport.

The research started with a large introduction phase to learn about biofuels and industrial symbiosis. To understand more than typical biofuel production issues and knowledge, a biofuel reference group was established with regional biofuel actors. The biofuel synergies reference group regularly met in order to discuss synergies, obstacles, future projects and more information related to integration and production processes.

It was decided that in order to “pick the brains” of the biofuel reference group and discover potential synergies several meetings were to be conducted using a collection of concepts from focus group interviews and brainstorming. This resulted in gatherings where synergies were the main topic. A wealth of empirical data was provided from the meetings including problems, potential synergies and their methods of portraying environmental performance. In particular, a biofuel synergy development meeting was held to develop potential synergies, which resulted in significant portion of the data used in this research.

The aforementioned data was used to produce a classification method which was originally thought to be used to study conditions for implementation of synergies. Article III and a more detailed research report were therefore written about the method for the classification with the primary aim to provide a method for the conditions for implementation of synergies. However, it was found that the classification method could be used for more applications in the project, namely describing individual synergies for industrial symbiosis and could be later applied for environmental performance and synergy mapping. A large literature review was performed to find how this methodology could benefit the industrial symbiosis literature. Article III was therefore revised as it was observed that it could be used as a means to describe further detail of individual synergies, which can provide an innovative new approach for the classification of exchanges for industrial symbiosis concepts. Remaining within the main scope of the project, the research remained primarily on the engineering aspects of

physical exchanges between the firms and did not focus on conditions or other social aspects of the exchanges.

Upon writing Article III, Articles I and II were then written which focused on providing an analysis and inventory of biofuel synergies and giving a background for the project to show how industrial symbiosis can be applied in the biofuel industry.

Article I can be seen as “*the background*” to the project to give context for further studies. A case study was conducted on a unique regional eco-industrial park on the island of Händelö in Norrköping with the primary goal of applying knowledge learned about industrial symbiosis and biofuel production processes using a case study of bioenergy firms. This was what could be considered “uncovering” the industrial symbiosis of Händelö. New concepts were also discovered from the case study, which are later used to describe how the biofuel industry could provide innovative concepts for the industrial symbiosis literature.

In order to provide more synergies and to expand the exchanges of Händelö and other biofuel firms worldwide, Article II provides an inventory of possible synergies. These synergies were identified for integrated biofuel synergies and external synergies pertaining to the application of material and energy exchanges. A classification of the types of industries involved in synergies were also applied in Article II, which can thereafter be further justified in Article III, even if it was written previous to Article II. The categories of industries involved in potential synergies with the biofuel industry were identified to offer justification for further symbiotic activities with external industries.

5.2 Biofuel and Industrial Symbiosis Literature

An extensive literature review was conducted to learn about biofuel production systems, synergies and industrial symbiosis. The first step of the literature review was to find relevant biofuel production information. Literature was reviewed on a number of topics ranging from innovative production techniques, current overviews of production, life cycle analyses of biofuel systems and reviews of raw materials for biofuel production. From the preceding chapter related to biofuel production, the material and energy flows have been provided as a result of the literature review. These flows are used to provide details for possible interaction with other biofuel production plants and external industries. Thereafter the focus of the biofuel literature was stressed on the use of potential synergies from biofuel production raw materials and outputs. An extensive description of the biofuel synergies literature review is provided in Article II appended to this text.

The field of industrial symbiosis and the concepts pertaining to it were thereafter a focus for literature review. Among the literature reviewed for industrial symbiosis were articles outlining the history of industrial symbiosis to classification techniques. Important concepts reviewed included by-product exchanges, utility exchanges, anchor tenants and classification methods for industrial symbiosis and industrial ecology. As taxonomy and classification are not always similar in the literature, an extensive review of the classification of industrial symbiosis was conducted, as outlined in Article III. This was done to later provide details to show that more detail for individual exchanges is needed.

5.3 Interviews and Focus Group Interviews

During the research, a total of 4 workshops were conducted with actors in the regional biofuel synergies reference group including Svensk Biogas AB, Tekniska Verken i Linköping AB, Ageratec AB and Lantmännen Agroetanol AB. This group represents a collection of actors with expert knowledge of biogas, biodiesel, ethanol as well as energy and infrastructural issues. The synergies reference group also contained 4 academic participants from the Division of Environmental Technology and Management of Linköping University, including 2 assistant professors, a professor and the author, a PhD candidate. The workshops were conducted much like focus group³ interviews, though some influence of brainstorming was also used. More detail is provided Articles II & III as well as in Martin et al (2009).

The aim of these workshops were to understand the conditions for synergies, actual synergies, potential synergies, learn of the biofuel processes, gain insight into the future actions of the firms and create a forum for the actors to meet and discuss synergies and share knowledge. The topics of the four meetings can be described as follows;

- Meeting 1- Introduction to the Project and First Brainstorming for Methods
- Meeting 2- Biofuel Synergies Development Workshop
- Meeting 3- Conditions for Implementation of Hypothetical Synergies
- Meeting 4- Implementation of Identified Potential Synergies

Data from the workshops were used in all articles, with the primary focus to identify potential synergies. To ensure quality of the data all of the meetings were recorded and later transcribed. Moreover, the sessions were conducted by a moderator, where the author acted primarily as a transcriber with the intention of learning about and registering all information provided by the group. This was done to ensure the group was not led in a biased manner. Thereafter several reports were produced and provided to the industries for review.

5.4 Field Visits

Included in the data collection were many observational field visits. These visits were primarily conducted in collaboration with the focus group meetings at the facilities of the biofuel actors, to introduce everyone involved in the meetings to the production techniques, processes and other details of each biofuel firm to spark interesting dialogues. Several additional visits were also conducted by the author and supervisor to gain supplementary information when needed about specific material and energy flows.

³ A focus group is defined as a small gathering of individuals, who have a common interest or characteristic, assembled by a moderator who uses the group and its interactions to gather information about a particular issue (Williams & Katz, 2001).

5.5 Using a Case Study

The aim of this research is to discover how industrial symbiosis can contribute to the biofuel industry and vice versa. In a sense, therefore these questions form the studied hypothesis. In order to answer these questions, case study research has been employed. Case studies, according to Yin (1994), typically answer the questions of “how” and “why.” Consequently, Yin (*ibid.*) also states that generalizations made from case study results are rarely considered applicable. However, case studies with marked empirical influences can support interdisciplinary research in many ways to support theory by comparing results, for the development of new theories and describe aggregate qualitative data in qualitative terms.

Correspondingly, Stake (1995) describes several types of case studies, ranging from intrinsic, instrumental and collective. These are defined respectively as those case studies which aim to understand a particular case better, those done to strengthen or weaken an issue or theory and those done to combine results from several instrumental cases. As this research has aimed at finding and supporting theories from literature and from the given cases, all three of Stake’s categories of case studies have been applied. The main case study of the research has been studied as an intrinsic case, however in the process, industrial symbiosis concepts have been reviewed against similar concepts and new concepts have been produced, therefore a good method of tying all of the methodological processes into one process is to use the method provided by Eisenhardt and Graebner (1989).

Again, as one hypothesis tested is to find how biofuel industries can provide new concepts for industrial symbiosis the work of Eisenhardt and Graebner (*ibid.*) has been used to review the development of data and theories presented throughout this thesis. Eisenhardt and Graebner (*ibid.*) consider and suggest pathways to analyze data similar to Stake (1995), but which can also lead the researcher to build theories and not simply follow structured methods. The method shows how systematic procedure in case studies can provide rigor, though there is also room for changes due to theoretical questions and aims changing during the research. A representation of how this approach has been conducted in this thesis can be seen in Table 1 below.

Table 1: Process of Building Theory from Case Study Research (Eisenhardt & Graebner, 1989)

Step	Activities	Motivation
Selection of Cases	<ul style="list-style-type: none"> • Specifying the system, boundaries and perspective 	<ul style="list-style-type: none"> • Focusing efforts to cases • Sharpens external validity • Specifying Population
Data Collection and Analysis	<ul style="list-style-type: none"> • Collecting data • Triangulation of Data • Pattern Matching • Explanation Building 	<ul style="list-style-type: none"> • Speeds up analysis through multiple data sources • Finding emergent themes • Gaining familiarity with data • Preliminary theories shaped
Shaping Theories and Enfolding Literature	<ul style="list-style-type: none"> • Developing hypotheses and shaping theories • Testing theories on other cases • Reviewing conflicting and similar literature • Reaching closure 	<ul style="list-style-type: none"> • Builds internal validity • Raises Theoretical Level • Sharpens Generalizability

The case study in this thesis has been conducted similar to Eisenhardt and Graebner’s (1989) method of building theories from case study research. This type of case study approach has the strength of generating creative insight from the concurrence of contradictory evidence from the data for application in the field. However, this method also can lead to an overly complex theory, i.e. theories which try to capture *everything* (ibid.).

First the employed case studies will be described using concepts related to industrial symbiosis, followed by a review of the data collection methods and thereafter an analysis of the data. Finally a review of the process used for the shaping of new concepts for the industrial symbiosis and biofuel fields has been provided. The ensuing sections will provide further detail into how the case study was reviewed, theories shaped, data gathered and quality ensured. Yin (1994) has been referenced in several cases to strengthen the decisions made for respective activities in the case study though under the structure of Eisenhardt and Graebner’s (1989) model.

5.5.1 Selection of Cases: Symbiosis Activities of Östergötland

Each case study serves as distinct analytical unit of an experiment. Analogous to laboratory experiments multiple cases and matching to literature is done in order to make replications, contrasts and extensions to emerging theories (Yin, 1994). The Händelö eco-industrial park has been chosen as the main case study for much of the concepts, ideas and applications used in this thesis as well as to match theories, support theories and even build theory.

The selection of Händelö as the main case study was done as several of the actors involved in the biofuel reference group are collaborating currently in what is called the “Bioenergy

Complex” currently on the island (Cleantech Östergötland, 2009; E.ON Värme Sverige, 2009). This case also is regional, offering a huge potential for field visits, interviews, etc. Due to the unique nature of the bioenergy firm exchanges it is used to exemplify industrial symbiosis concepts applied to a real world case.

Symbiotic activities of firms located in Linköping, Sweden (in the county of Östergötland, the same as Händelö) have also been referenced in the text. These have also been studied simultaneously to those of Händelö. This is due to the firms yet again being part of the research project and the nature of the exchanges involved. Moreover in order to build upon some of the concepts produced later in the text, comparisons will be drawn to this system but also to worldwide biofuel production systems with unique material and energy exchanges, or lack thereof.

5.5.2 Data Collection and Analysis

Information for the case study described above was provided from a number of sources ranging from field visits to focus group interviews. The data collection methods are described more exhaustively in the preceding sections. The sources of data include:

- Documentation of Synergistic Activities in the Region
- Focus Group Interviews
- Field Visits
- Direct Observation.

As a result of the data collection the analysis of the data was conducted through a triangulation, i.e. compilation of data, for the analysis of the case study (Stake, 1995). Triangulation is described as a means to provide more convincing and accurate data by providing multiple sources for data analysis. The subsequently described case study has therefore been produced from a number of data sources.

To describe the case with the concepts of industrial symbiosis the synergies were related to respective concepts. This was done by what Yin (1994) refers to as explanation building and pattern matching, the former of which is done to explain a case based on predisposed concepts. However, explanation building is typically related to how or why something happens. In this case however, it has been used together with pattern matching to describe the case in the context of industrial symbiosis.

5.5.3 Shaping Theories and Enfolding Literature

Interestingly, it was originally assumed that the biofuel industry could benefit from the theories of industrial symbiosis and not the contrary. However, upon review and analysis of the data new concepts emerged which led to new concepts for the industrial symbiosis field from application in the biofuel industry.

From the information provided on the concepts of industrial symbiosis, application of these concepts in the biofuel industries did not entirely conform. New concepts were thereafter tested and reviewed with existing industrial symbiosis literature for concepts such as the provision of geographic proximity and detail of individual synergies.

From the inventory of synergies it became apparent that biogas and biodiesel were frequently cited as potential acceptors of waste products from a number of industries. These cross-case

patterns emerged as a result of the analysis which ultimately led to the development of a new concept, though literature of the area must be reviewed. Theory-building researchers also typically use multiple data collection methods and triangulation (Eisenhardt & Graebner, 1989) to find new theories and test them with existing literature to conduct what is called the *unfolding of data*. Therefore, concepts on the theory of cradle to cradle and recycling were compared and subsequently added to that of industrial symbiosis to provide the context for this type of exchange and actor, from which the concept of upcycling tenant has been illustrated. Other concepts brought forward by this research have been conducted in a similar manner.

Yin (1994), beyond Eisenhardt and Graebner (1989), recommends that the data be generalizable in other areas; not only case specific. Two examples have there for been shown to support the concepts produced, i.e. Linköping and Norrköping. As this is a regional approach, the analytic generalizations brought forward may be criticized. However, to show how these can be used described beyond the borders, one can take case studies from other industries and other examples worldwide. Examples have thus been provided in relevant sections in order to describe how concepts can be analytically generalized from the empirical data beyond the regional study.

Once new theories and concepts have been found and tested, it is thereafter important to reach closure in the development of new ideas from the data provided. This can be done when theoretical saturation is reached, i.e. incremental improvements come to a minimum (ibid.). Several other new concepts were also thought of in this research, though their context provided minimal improvements and importance for this research project. Only concepts directly related to this research projects and the predefined scope have been reviewed.

5.6 Contribution of Appended Articles and Methods Employed

Each appended article has a distinctive contribution to this thesis. As described previously, although the articles were not written in the chronological order that they are appended, their content works in synergy to provide the retrospective results which lead to the view of how industrial symbiosis and the biofuel industry can mutually benefit from one another.

Article I was written with the aim to develop and define the research area further. As presented in the article, the application of industrial symbiosis in the biofuel industry shows how exchanges of by-products and energy could allow for improved environmental performance and efficiency. This is done through the use of a literature review on the topic of biofuels, industrial symbiosis and applying data obtained for a regional case study. From the case study new concepts for industrial symbiosis emerged.

Article II was written with the intention of expanding the author's knowledge of biofuel synergies from the previously described focus group interviews with a systematic literature review. The systematic literature review was conducted to find what further potential synergies were available in the literature. Thereafter, analysis of the data showed that there were typical industries which could be potential biofuel industry partners for the mutual exchange of materials and energy exchanges, i.e. by-product exchanges.

Article III was written to show the need for further details of individual exchanges in the industrial symbiosis literature. Data from the focus group workshop was used to construct a classification method for biofuel synergies which provided added details for individual exchanges between biofuel industries and external industries.

Table 2: Contribution and Methods used in Appended Articles

Article	Methods Used	Contribution to thesis
I	<ul style="list-style-type: none"> • Literature Review of Biofuels • Literature Review of Industrial Symbiosis Concepts • Case Study of Händelö • Theory Building based on analysis of case study 	Describes biofuel production synergies and how industrial symbiosis can be applied for increased efficiency and environmental performance. Concepts such as the energy system and the use of biofuels as an upcycling tenant are described.
II	<ul style="list-style-type: none"> • Systematic Literature Review of Biofuel Synergies • Focus Group from Biofuel Synergies Development Workshop 	An inventory of biofuel synergies with other biofuel firms and external industries. The article additionally provides characteristics of these synergies, e.g. industries involved and that by-product synergies are the most prevalent.
III	<ul style="list-style-type: none"> • Literature Review of Industrial Symbiosis Concepts • Focus Group Data from Biofuel Synergies Development Workshop 	Describes the need for detail individual exchanges in industrial symbiosis. The classification method used as a way to “create a language” for describing synergies.

6 RESULTS

The research conducted for this thesis has provided data spanning the fields of biofuel production and industrial symbiosis. In order to provide more resolution to how these correlate, the results have been portrayed by exemplifying synergies between biofuels and external industries and showing how the theories of industrial symbiosis have been applied to the biofuel industry.

The application of industrial symbiosis concepts have been employed in several approaches in this text. A case study of Händelö has been analyzed to show the flow of by-product and utility synergies. Industrial symbiosis concepts are thereafter related to the characteristics of Händelö. Linköping's unique symbiotic activities for biogas production will also be outlined further. Thereafter, an inventory of synergies produced from several portions of the research project has been included. These synergies show how biofuel industries can integrate and even integrate with other industries. Based upon the findings of the inventory, a review of industrial symbiosis concepts and how a classification method for synergies can provide further details of individual synergies for industrial symbiosis literature has been presented.

Section 6.1 is based entirely on research provided from Article I. The subsequent section, 6.2 is based on data collection from the regional exchanges of material and energy and is not described in the appended articles. Section 6.3 is based upon findings from Articles II and III. To conclude, section 6.4 is based upon the results from Article III.

6.1 Händelö as an Example of Industrial Symbiosis Applied in the Biofuel Industry

The eco-industrial park on the island of Händelö, Norrköping centered around the production of bioenergy is an example of industrial symbiosis applied to the biofuel industry. Many of the concepts of industrial symbiosis can be identified from the exchanges and collaboration these firms encompass.

The combined heat and power plant of E.ON provides necessary energy for many processes and households. A large portion of the energy requirements for the ethanol plant are provided for by E.ON. The utility synergies between Agroetanol and E.ON are delivered in the form of pressurized steam and electricity (Amiri et al., 2009). Electricity and district heating are also delivered to the municipality (E.ON Värme Sverige, 2009). In return, the municipality sends refuse to be combusted in the combined heat and power plant along with biomass wastes provided by the paper industry, located on the same island (Cleantech Östergötland, 2009; E.ON Värme Sverige, 2009). As the energy provider, E.ON can be identified as the anchor tenant of the Händelö symbiotic network of bioenergy.

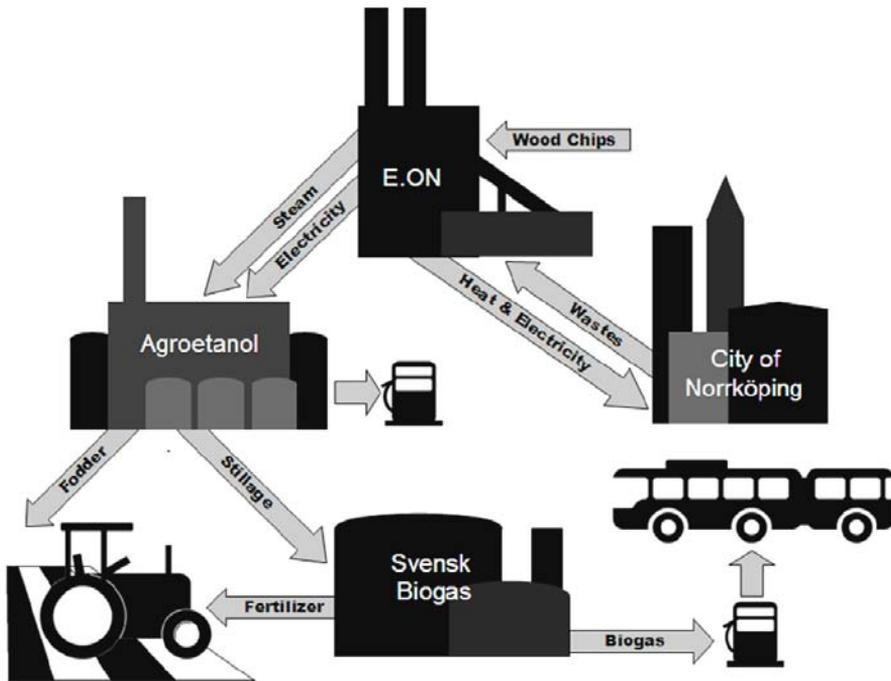


Figure 4: Händelö Bioenergy Symbiosis

The ethanol plant of Agroetanol produces ethanol from cereals, of which a portion comes from the region of Östergötland. The ethanol is then sent to a neighboring port and storage facility of a national petroleum industry; which is used primarily for low-blends in Swedish petroleum. Once the ethanol is produced, the stillage is made into fodder with various dry matter contents (Lantmännen Agroetanol AB, 2009a; Lantmännen Agroetanol AB, 2009b). The fodder is then used by dairy and livestock farmers. A portion of the thin stillage, also known as syrup, and filtered hulls, straw and crushed kernels are thereafter trucked to the neighboring biogas facility to supply the anaerobic digesters with feedstock; an important by-product exchange. Interestingly, the stillage is sent warm, at a temperature around 80°C, and therefore carries all the energy needed with it to run the biogas process at around 38°C. It could then be also classified as a utility synergy. Furthermore, a portion of the syrup is also sent to the biogas production facility in Linköping by truck, incorporating a regional by-product exchange (ibid.).

The biogas plant produces biogas for regional transport requirements. Through the process of removing methane, the nutrients from the organic material are left behind in the by-product, digestate. Biogas production consequently allows for the production of energy and a fertilizer while removing a harmful greenhouse gas to be used for energy purposes. However, the digestate may also be used as feed, combusted directly or made into energy pellets. The by-product of biogas production on Händelö, digestate, is stored before it is used as a valuable bio-fertilizer by regional farmers. The bio-fertilizer meets the highest sustainable criteria for the Swedish eco-label, KRAV (Svensk Biogas AB, 2009). Biogas digestate is therefore used for by-product exchange synergies with external industries.

6.2 Linköping: Symbiotic Activities for Biogas Production

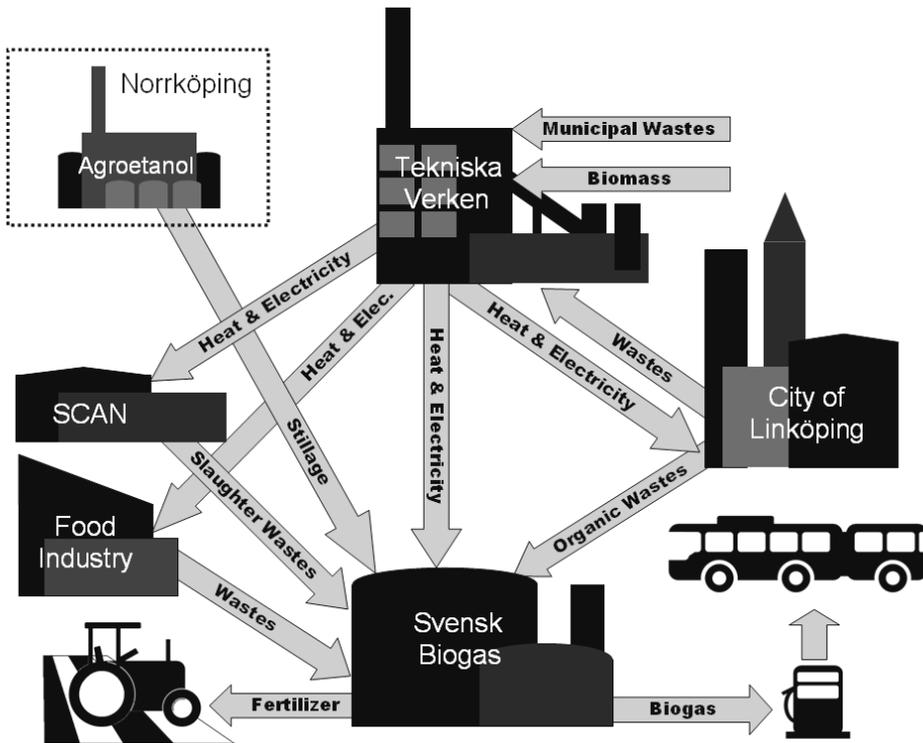


Figure 7: Linköping Biogas Production and Synergies

As a portion of the syrup produced from Agroetanol in Norrköping makes its way to Linköping for the production of biogas, the unique by-product synergies involved in biogas production will be described in the ensuing text.

In Linköping, biogas is produced from a literal “smörgåsbord” of inputs. Figure 7 above visualizes some of the exchanges within the city, and including the syrup from Norrköping. However, many more inputs are also included which are not shown. As the food industry, primarily meat and dairy products, is a prominent industry within the city, many of the by-products and hard to dispose of waste are delivered to the biogas production plant in the city for anaerobic digestion as by-product synergies (IEA, 2008; Linköpings kommun, 2008). Food wastes are also collected at a number of restaurants and hotels throughout the city destined for the biogas plant. These materials are then homogenized before entering the anaerobic digestion chambers to produce biogas for public transport and personal vehicles (Linköpings kommun, 2008; Svensk Biogas AB, 2009). Similar to Norrköping, the digestate can be used as fertilizer due to the homogenization to kill any harmful substances in the organic material before anaerobic digestion. Heat and electricity for the production for the biogas plant and many other firms come from the utilities provided by the closely located CHP plant at Gärstad Verket which is fuelled by municipal wastes, biomass and sorted wood wastes from the city and other municipalities (Tekniska Verken i Linköping AB, 2010).

6.3 Inventory of Synergies and Characteristic Exchanges and Industries

Synergies and integration of biofuel and energy firms are not only limited to the example provided in the previous text. Many more synergies have also been identified, and can be applied for further expansion of cases such as Händelö or to expand individual biofuel production plants. This could be done by reviewing the material and energy flows and finding appropriate synergies.

A total of 148 synergies were produced from the combination of a literature review study and from a previous synergy development workshop. Tables 2-4 of the appended Article II show a compilation of 95 unique synergies, i.e. non repeated and relevant synergies. A selected few of the synergies have been listed in the proceeding table to show the synergies between biofuel production and external industries.

Table 3: Selected Synergies between Biofuel and External Industries

Biofuel → Biofuel Synergy	Industry
Gas produced at Ethanol Producer sent to Biogas Producer for upgrading	Biogas
Glycerol produced from biodiesel production for biogas production	Biogas
Corn Oil for biodiesel production	Biodiesel
Ethanol stillage as biogas source	Biogas
Biofuel → External Synergies	Industry
Dry stillage for biofertilizer	Agriculture
Biodiesel used as remediation agent for treatment of oil spills	Env. Services
DDGS used as filler for bioplastics	Materials/Building
Glycerol added to gasoline as fuel extender	Energy/Fuel
External → Biofuel Synergies	Industry
Potato Chip/Snack Food waste vegetable oil (WVO) used for biodiesel production	Food/Feed
Municipal solid wastes as biogas residue	Municipal
Household wastes for ethanol production (fruits, shells, etc.)	Municipal
Carbon dioxide from biogas upgrading for greenhouses/plant source	Greenhouse

It can be seen that the synergies range in the type, i.e. either as a by-product or utility synergy and also one can see the industries involved in potential cooperation. Of the synergies produced those relating to the process integrations between biofuel industries have been identified as a common occurrence. Additionally, many synergies also exist between the biofuel industry and external industries.

Notably the inventory uncovered more synergies than those uncovered through the biofuel synergy development meeting. Moreover, numerous synergies mentioned by the biofuel synergy reference group were also found in the literature.

6.3.1 Integrating the Biofuel Industry

Many synergies have been outlined from the research which deals with the integration of production processes between biofuel firms. By this, it is meant that biofuel firms can cooperate with other biofuel firms in the exchange of by-products and utilities. The interactions include those between the three identified biofuel types for this thesis; biodiesel, biogas and ethanol.

Biodiesel-Bioethanol Synergies

Several synergies between the production processes of biodiesel and bioethanol have been identified. These include the use of ethanol or other alcohols produced from the ethanol production process in place of methanol for the transesterification reaction for biodiesel production. By-products from the ethanol production process can also be used for biodiesel production. This includes fats from corn and wheat crops. Moreover, as ethanol production demands much higher temperatures and energy inputs, waste heat could be used in the much less demanding biodiesel process.

Biogas-Biodiesel Synergies

Biodiesel production by-products are common inputs to biogas systems. Glycerol has been documented as a valuable input to the anaerobic digestion process, enhancing methane output dramatically. In addition seedcake from the pressing for oils can be used in biogas production.

Biogas-Ethanol Synergies

Of the synergies included between biofuels, synergies between the biogas and ethanol production processes are the most abundant, several of which are being currently employed at the eco-industrial park of Händelö. Many of these synergies originate from ethanol by-products used as raw materials for biogas processing. Among the synergies DDGS, thin stillage and syrup of fermentation process of ethanol production can be used as inputs to the biogas digestion process. Moreover, waste heat from the more energy demanding process of ethanol can be used in the biogas process. Interestingly, ethanol production waste water treatment also has the potential to be exploited to produce biogas. This biogas has been proposed to be upgraded at a co-located biogas plant.

6.3.2 Biofuel Industry Integration with External Industries

Aside from the synergies between biofuel industries, many synergies between biofuel and external industries have been identified. These synergies encompass an extensive variety of characteristics and include methods to handle biofuel production by-products, add new raw materials for biofuel production and even supply utilities for the biofuel industry. Table 4 below shows some of the industries involved in potential synergies with the biofuel industry.

Table 4: Biofuel and External Industry Synergistic Possibilities

<i>Biofuel Industry Interactions</i>	<i>External Industry Interactions</i>
<ul style="list-style-type: none"> • Biogas • Biodiesel • Ethanol 	<ul style="list-style-type: none"> • Food and Feed Industry • Municipalities • Energy and Fuel Production Industry • Agricultural Industry • Chemical and Cosmetics Industry • Greenhouses • Environmental Services Industry • Materials and Building Supply Industry • Forestry and Paper Industry • Algae Production

Integration with external industries can imply new cooperating industries and feedstocks for biofuel production. The synergies identified exist between a wide range of external industries. Table 5 below shows a quantification of synergies discovered for potential partnership with the biofuel industry.

Table 5: Interaction with Biofuel and External Industries

Category	Number of Synergies
Food/Feed	21
Biogas	12
Energy/Fuel	10
Municipal	9
Biodiesel	8
Algae	6
Chemical/Cosmetics	6
Agriculture	5
Ethanol	5
Greenhouse	4
Environmental Services	3
Materials/Building	3
Biofuel General	2
Forestry/Paper	2

The food and feed industry has been identified as a potential partner for the biofuel industry. By-products from the biofuel industry, such as glycerol, DDGS, seedcake and even dried biogas digestate can be used as feed or fodder. Applications range from animal to human feed. Comparatively, food industry by-products can be used as raw materials for biofuel production. Examples include using waste frying oils for biodiesel production and dairy wastes for biogas or ethanol production (i.e. with lactase).

Other interactions with external industries include those with the greenhouse industry, municipalities and energy production plants. Biofuels can receive many inputs from the regional municipalities. Some of the synergies identified include the use of sewage sludge for

biogas and biodiesel production and municipal wastes as biogas and bioethanol inputs. Outputs from the biofuel industry can also be used in the municipality, including waste heat for swimming pools and by-products used as carbon filters. Furthermore, as a result of the production of ethanol and biogas, carbon dioxide is released into the atmosphere. Many synergies have therefore been indentified to handle this CO₂, including sending the CO₂ for greenhouses, algae production, cooling systems and even beverages. Energy industries can also make use the biofuels or by-products for the production of electricity and heat. Biomass wastes and other by-products like glycerol, seedcake and unwanted biomass from produced during the separation of wheat kernels at the ethanol facility can be used for energy production through combustion.

A more extensive listing of synergies is provided in Article II. Further examples of some synergies identified between the biofuel and external industries in Article II include:

- Biogas digestate as a bio-fertilizer
- Biodiesel as a remediation agent for oil spills
- Animal fats from slaughterhouses used for biodiesel and/or biogas production
- DDGS used as a filler in building materials

6.3.3 By-Product vs. Utility Synergies

As aforementioned an array of synergies are present to make use of by-products from external and biofuel industries for many purposes. Of these synergies those related to by-product exchanges are most apparent. Those related to utility exchanges however are not as common from the study. In some cases it is difficult to classifying a synergy as a by-product or utility synergy. This is due to the context of the material or energy being exchanged, as the synergy may be classified as a by-product from one industry but used as an utility at the destination. Table 6 below shows the number of synergies identified from Article II relating to by-product and utility synergies.

Table 6: By-product vs. Utility Synergies

	By-Product Synergies	Utility Synergies
Synergies Brainstorming	52	7
Literature Review	35	1
<i>Total</i>	87	8

The previous section outlines many of the by-product synergies between biofuels and external industries. Examples of utility synergies from the study include using waste products for energy purposes and employing of waste heat and water in subsequent industries.

synergies, Article III provides a means to classify synergies according to their interaction within the biofuel industry and with external industries. Thereafter, further details are also included in the method. The origin and destination of the synergy is described. This is done due to the fact that definitions of by-product and utility synergies may not always apply to the exchanges and may not be mutually exclusive depending on the context of the firms. This has been built into the classification method. It is believed that documentation of the individual linkages within symbiotic networks could therefore lead to more details which can provide the framework for analyses of the environmental and economic performance of industrial symbiosis networks. Figure 8 below shows a review of the classification method. More information on how the method is used to describe individual exchanges can be obtained from the appended Article III.

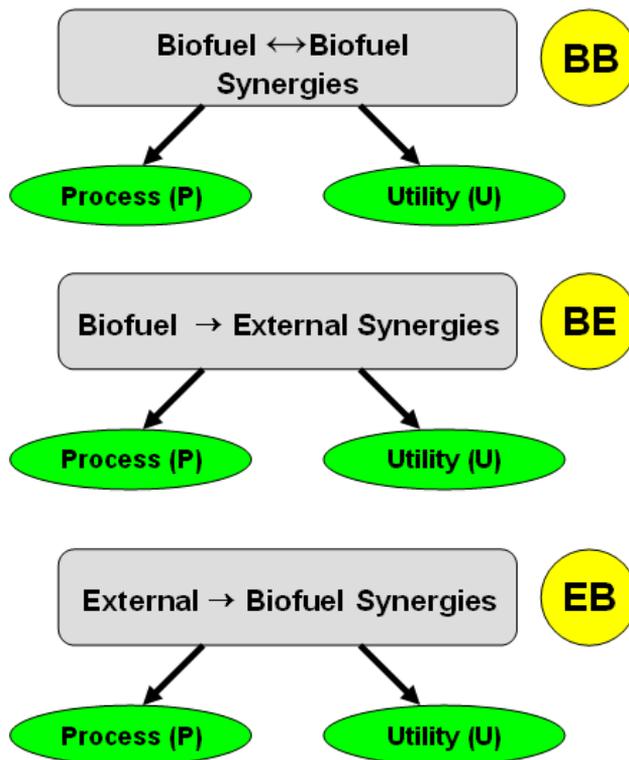


Figure 8: Classification Tool for Biofuel Synergies

7 HOW CAN THE BIOFUEL INDUSTRY BENEFIT FROM CONCEPTS OF INDUSTRIAL SYMBIOSIS?

While many reports look toward the limitations of first generation biofuels, industrial symbiosis can allow for the potential development of the biofuel industry. By viewing the system as indefinitely connected to the surrounding systems and looking for means to optimize material and energy flows, biofuels can gain many advantages over the current debate about their efficiency, emissions and other factors. Expanding the system boundaries will allow for increased cooperation and a wider range of material and energy inputs and outputs. Many potential synergies have been uncovered which can integrate biofuel firms; though biofuel firms may also integrate with external industries.

This chapter is based on results from Articles I-III as well as some of the results from this thesis and is approached based upon the activities outlined in the methodology chapter titled, “Data Collection and Analysis” and “Shaping Theories and Enfolding Literature.”

7.1 More Effective Material and Energy Flows

Industrial symbiosis offers the biofuel industry with methods to reduce the flow of materials and energy. By viewing the system as flows of material and energy, these flows can be made more efficient to reduce, reuse and even eliminate them.

As reported, many biofuel systems are criticized for poor environmental performance and energy efficiency. Many of the “poor” systems have been outlined with linear flows of materials and products. However, an ethanol plant is not only an ethanol plant. Lantmännen Agroetanol AB is an example of an ethanol plant that is complementary to this, a fodder plant. The Swedish Farmers’ Cooperative, Lantmännen, provide the ethanol plant with cereals for ethanol production, ethanol is produced and thereafter fodder is produced for the corresponding farmers’ cooperative. This is an example of keeping the materials within an organization and along with the many additional outputs shows that ethanol plants do not only provide linear flows of materials. Moreover, the use of renewable energy from biomass and other wastes provides increased motivation for the improvement of biofuel energy efficiency. The waste of one biofuel firm can become the necessary input to another biofuel industry, thus making the venture more efficient and adding to the performance of both products under question. These examples are not only regionally applicable and can be conducted worldwide.

It has also been shown that synergies with external industries can provide additional inputs of raw materials for biofuel production. While biofuels are criticized for using virgin crops to produce fuel, emphasis is now being put on the use of waste materials for biofuel production, reducing the impact for biofuel production and sharing the load with the precedent use for the crops, biomass and organic matter. This opens for a wider range of raw materials, and is apparent in all biofuel production processes worldwide, not only the regional cases in this text.

7.2 New Raw Materials and Markets for By-Products and Utilities

The outlined example of the island of Händelö is a remarkable example of industrial symbiosis applied in the biofuels industry. This eco-industrial park literally supports the term “island of sustainability.” However, given the large number of synergies identified in the preceding sections exchanges can be expanded for further developments on the island. This will allow for increased integration with other industries on the island, more efficient biofuel production, common infrastructure, cooperation (not competition) and cascading of materials to extract essential components and energy.

By conducting a review of the material and energy exchanges on the island, many potential synergies can be identified to the corresponding inventory of synergies in Article II. As an example, biogas produced from the wastewater treatment of Agroetanol can be upgraded by Svensk Biogas. Furthermore, stillage is supplied to Svensk Biogas by truck. As the plants are literally neighboring, a pipeline could be built to integrate utility infrastructure and open for more synergies. In the future it is hoped that a biodiesel producer will also establish itself on the island of Händelö. The biodiesel producer would act as a reference case for Ageratec of Norrköping which produces biodiesel production equipment from small to industrial scale applications. As a result of the biodiesel production further synergies could be established on the island. Ethanol could be used in place of the commonly employed methanol. Glycerol, the main by-product of biodiesel production, could then be used either as an input into the biogas process or used as an additive in the nearby fuel distribution industry. Beyond these synergies, more materials and energy could be discovered in the Östergötland region for biofuel production, e.g. for further synergies from the industrial waste of food industries in Linköping.

Synergies outside the bioenergy firms also are possible. An interesting option is to take the CO₂ from E.ON, Agroetanol and Svensk Biogas and use it for subsequent processing for greenhouses, algae, beverages, cooling applications, etc. Additionally, located on the same island is a large paper industry for which potential synergies can be identified to further increase utility and by-product exchanges on the island and beyond. Food industries, the municipality of Norrköping and further synergies between the biofuel plants and E.ON could be achieved.

Using the concepts of industrial symbiosis, biofuel production may expand beyond the current supplies of material and energy. Identifying potential partners as portrayed in Table 2 above can offer options for new raw materials and allow for innovative approaches for biofuel production. Biofuels may therefore diversify their base of raw materials to ensure a technological lock-in does not occur. Yang and Feng (2008) agree with this strategy and believe that diversification of raw materials and exchanges allow for growth with different but related industries.

7.3 The Anchor Tenant as a Supplier of Renewable Energy

An anchor tenant, such as E.ON on the island of Händelö, provides the necessary utilities for the eco-industrial park of bioenergy firms, including biofuels and the forest industry. The anchor tenant here thus acts as the energy supplier to the system, and may be the motive for the collocation of other industries. In this research project energy systems have been identified as one of the prominent factors for the environmental performance of biofuel production. While several plants in the United States exhibit poor energy efficiency due to fossil energy inputs (Börjesson, 2004), many plants, including the exemplified Händelö allow for better energy efficiency. This is due in part to the collocation of the energy supply and the use of renewable energy. Renewable energy thus provides improved environmental performance for the collocated industries making use of the utilities provided by the energy production plant. Börjesson (2009) correspondingly identifies a substantial reduction of greenhouse gas emissions when using natural gas as an alternative to coal in the production of ethanol. Emissions are reduced further when energy is delivered through the combustion of biogas and the harvested wastes of ethanol crops.

7.4 Expanding System Boundaries to Improve Environmental Performance and Energy Efficiency

As outlined in the examples from the previous sections concerning more effective flows of raw material and energy flows and the use of an energy provider, the biofuel industry can benefit from industrial symbiosis concepts. Viewing these in retrospect offers the ability to see that one must observe the entire biofuel life cycle and expand the system boundaries to find increased synergies. Although this research is primarily focused upon the production aspects, many more synergies can also be found in the agricultural, employment and infrastructural phases. However, viewing the energy system and material flows can offer drastic improvements for biofuel production.

An example, as aforementioned, by using the energy system of E.ON, and taking into account the by-products produced from the ethanol plant of Lantmännen Agroetanol AB an energy balance of nearly 1:5 has been achieved (Börjesson, 2006; E.ON Värme Sverige, 2009; Lantmännen Agroetanol AB, 2009a). System expansion accounts for the use of the by-products and allocation of fossil energy used to replace these with alternatives. In the example provided above, the reduction of soy meal imports from abroad by protein fodder produced by Lantmännen Agroetanol AB is accounted for. However, not all by-products have been accounted for in the example described. If the system is expanded further to include using the additional alcohols for carbon filtering sources, biogas produced from the WWTP for internal energy and most importantly carbon dioxide for use in various applications the environmental performance and energy efficiency could be increased even further.

7.5 Material and Energy Cascading

As aforementioned, the use of all by-products and portions from the feedstock is becoming to improve energy efficiency and environmental performance. Similar to using all by-products, the use of all portions of the raw material inputs to the best possible means is highlighted in industrial ecology and symbiosis research; *material and energy cascading*. Many of the synergies identified use some fraction of material inputs and outputs. Biofuels only extract a fraction of the feedstocks to produce fuels. Moreover, many reports and synergies identified in the inventory illustrate that biofuels can be made from many of the waste products from other industries. Instead of speaking of competition with other industries, biofuels may be made from a fraction of material inputs and in many cases using wastes.

Materials can be cascaded to allow for a wider range of products from material inputs, and not simply a linear model of crop in, biofuel out. As an example, and as outlined in the synergies inventory, wheat or corn used for ethanol production can be used for many purposes, beyond just ethanol production. The DDGS and other parts of the wheat and corn kernels are valuable output for animal feed, but they can be used for human food and chemical applications. Problems arise and do not permit these to be used for human applications due to the many steps of the ethanol production. Therefore, by cascading the material and extracting all the protein and other valuable components, ethanol can then be produced from the leftovers and the remaining carbohydrates used for fermentation. Similar applications of cascading can be applied in the use of energy between industries for the greater efficiency in the biofuel production process. Cascading of materials and energy could allow for greater economy, environmental performance and energy efficiency in the processes.

8 HOW CAN INDUSTRIAL SYMBIOSIS BENEFIT FROM THE APPLICATION OF BIOFUELS?

The application of the biofuels and the biofuel industry in the industrial symbiosis context is a rather new development, although it can add a lot to the development of the industrial symbiosis field. As aforementioned, many reports regard biofuels as limited, while industrial symbiosis applications can allow biofuels to gain further potential. However, by using biofuels as an example and applying the concepts of industrial symbiosis new innovations can transpire. Most important of all, biofuels can innovate industrial symbiosis.

In many of the topics described in the chapter on industrial symbiosis, only a limited quantity of the knowledge can be applied and utilized in the biofuel industry. In many cases in this thesis, information has been “transformed” to provide new categorization and concepts to describe the activities and integration the biofuel industry currently encompasses. These innovative approaches for industrial symbiosis can be applied in many other fields, though the context must be taken into account. The forestry industry, for example, could use many of the new concepts provided in this thesis. Of these, the broadening of industrial symbiosis to include “virtual borders,” adding an *upcycling tenant* to give further value and use to wastes as well as providing more details into the individual exchanges for industrial symbiosis literature have been outlined in this thesis.

Similar to Chapter 7, this chapter is based on results from Articles I-III as well as some of the results from this thesis. It is approached based upon the activities outlined in the methodology chapter titled, “Data Collection and Analysis” and “Shaping Theories and Enfolding Literature” as some patterns and new concepts have been discovered.

8.1 Biofuels as Upcycling Tenants

One important element of industrial symbiosis concepts is the understanding of reasons and success factors for the actors involved in a symbiotic network. Of those actors, an anchor tenant can provide the necessary foundation for cooperation and consequently result in the improvement of environmental performance for all firms in symbiosis. Outlined in this work is another important actor; the upcycling⁴ or upgrading tenant.

In this thesis, a biogas plant acts as an upcycler of materials and can attract industries with troubles related to the treatment of their wastes. These difficult to dispose wastes could then be used to produce additional products which subsequently can deliver back energy and gas for internal processes. Many eco-industrial parks send wastes organic wastes to be combusted. However, the wastes could produce methane, and can even later be combusted. As an example, slaughterhouse wastes in the city of Linköping are sent to the local biogas facilities for disposal. Mutual benefits are then created between the slaughterhouse industry and the

⁴ *An upcycling tenant could be defined as an industry which takes and consumes wastes and by-products from several other industries to either add value, produce energy and/or create a new valuable product. Simultaneously the upcycling/upgrading tenant provides improved environmental performance for its suppliers of raw materials.*

municipality in the form of biogas for municipal transport and vehicle fuel for the community (IEA, 2008; Svensk Biogas AB, 2009). Materials are therefore cascaded to obtain and extract important components before subsequent processing.

Correspondingly, biodiesel production plants may also be considered upcyclers of materials, as they have the possibility to handle previously difficult to dispose of materials and upgrade them to products similar to biogas (Angerbauer et al., 2008; Chung et al., 2009; Haas, 2005; Lin & Li, 2009; Pokoo-Aikins et al., 2010; Saunders & Rosentrater, 2009).

An upcycling tenant can give further value to wastes and even provide energy for the firms in the symbiotic activity. This upcycling tenant could accordingly be a key actor in an industrial symbiosis park and, much like an anchor tenant attract other industries, which would then open for other by-product and utility synergies between them.

8.2 Geographic perspective

Common to many industries are the trade and shipment of raw materials, by-products and wastes on a worldwide market. Biofuels are no exception to this and many of the inputs and outputs to the biofuel industry are not guaranteed to be provided from defined sources; sources vary based on market values, pricing, agricultural conditions, etc. However there are many established links in the trade of the raw materials for biofuels and their by-products worldwide. These established partners can be regional or international, though their goal is to produce and provide something to the biofuel industry.

An issue therefore to overcome is how to involve the exchange of by-products and raw materials as “industrial symbiosis” in the biofuel industry. Chertow describes industrial symbiosis as defined by geographical proximity; however there is also inference to how eco-industrial parks can collaborate within a “virtual” border. The biofuel industry can offer one example of this “virtual eco-industrial park.” Exchanges over distance could be attractive and offer better possibilities for the handling of wastes (Christensen & Kjaer, 2009). Therefore, it is proposed that in some industries, certain outliers could be acceptable and included in an eco-industrial park.

8.3 Additional Details for Individual Exchanges

Whereas much of the industrial symbiosis literature illustrates the occurrence of industrial symbiosis in aggregate, rarely individual exchanges are described in more detail. The CECP (2007) opened for this, by arguing that further classification of exchanges must be made on the grounds of whether the exchanges were considered by-product, utility or management synergies. However, the definitions are not mutually exclusive, and some synergies labeled as a by-product of one firm, may in fact be classified as a utility by another. Due to this, in Article III, a new method for the classification of synergies has been proposed. This method adopts a classification based on the origination and destination of the synergies. The synergies can therefore be labeled as a by-product or utility respective to the origination or destination. Moreover, to go a step further, the synergies take place between a main industry or firm and an external industry or firm. This can also be documented and using notation, one can reveal more details about the synergies in question. For example, it can become apparent that

between biofuel industries, utility synergies are most prominent and integration could be produced.

This can even open up for further research, for example into the implementation of synergies, to document success factors and find methods to prioritize synergies for better environmental performance. By classifying the flow of materials and energy as such we may permit for the investigation of the correlation between the nature of the synergies with other factors, such as driving factors, implementation factors, geographical details, etc. which would benefit the industrial symbiosis field.

8.4 Products as Synergies

Typically in the field of industrial symbiosis products are not considered for exchanges as synergies. However, in the biofuels industry and in this research project, biofuels have been considered for symbiotic activities. As an example, ethanol used for the transesterification reaction for biodiesel production is considered a synergy between the biodiesel and bioethanol firms. Furthermore, the fuels themselves, such as biodiesel, have also been identified as remediation agents, again showing that a product is used as a synergy. While this is not customary, perhaps products may be included for future synergies. Nevertheless, the products are generally considered “good” if they are used regionally. Individual products may therefore attract other firms.

8.5 Using Renewable Energy for Industrial Symbiosis

Literature from the field of industrial symbiosis covers many activities worldwide. In recent years there has been a great number of these activities “uncovered” to give the industrial symbiosis community further systems of reference and to describe unique exchanges (Chertow, 2007; Van Berkel, 2009). However, as mentioned previously, many of these systems are based on the use of fossil energy; renewable energy systems are seldom described.

Nonetheless, Wolf and Petersson (2007) as well as Korhonen et al. (2001) describe how renewable energy in the forestry industry may offer increased improvements in environmental performance due to the use of biomass. Correspondingly, Christensen and Kjaer (2009) describe how integration for the production of biofuels and energy from biomass wastes may link many firms in various industries; including the agricultural, forestry, manufacturing, food and energy production industries.

This thesis and appended articles have provided yet more examples of renewable energy employed in symbiotic activities which could provide further information for the field of industrial symbiosis for exploration of many interesting questions. These could include questions of whether the systems would be *better* with renewable energy and how the synergies would be different with renewable energy systems. Furthermore, examples such as those in this thesis could be used for portraying industrial symbiosis to preclude questions about the use of fossil fuels in systems such as Kalundborg.

9 CONCLUSIONS

The aim of this thesis has been to apply the concepts of industrial symbiosis to the biofuel industry. This was conducted to find the possibilities for integration, new raw materials and to provide a systems perspective to biofuel production industries. However, it has also been discovered that using the application of biofuels to describe industrial symbiosis concepts can offer many benefits for the field of industrial symbiosis.

9.1 Biofuels Benefiting from the Field of Industrial Symbiosis and Relevant Concepts

Applying industrial symbiosis concepts to the field of biofuels offers an insight to expand the system boundaries and provide energy and material optimizations. Implementation of these concepts could lead to many benefits for the biofuel industry, including the following.

- The energy systems used for biofuel production are very important. Reduced impacts and energy efficiency can be realized if energy systems are fuelled with renewable fuels. A CHP plant using biomass wastes from biofuel feedstock harvesting may add to further benefits.
- A large quantity of descriptions of potential synergies between biofuel firms and external industries exist in the literature. These can be used to search for future by-product and utility exchanges for symbiotic activities between biofuel and external industries.
- Biofuel production plants may share many potential by-product and utility synergies and can be integrated. Moreover, many synergies also exist between the biofuel industry and external industry. This is especially true for interactions between biofuel industries as well as the food industry, municipalities and the chemical and cosmetics industry. It is important to therefore view potential synergies to find prospective partners for the realization of by-product and utility synergies.
- The example of Händelö provides a view of industrial symbiosis concepts applied to the biofuel industry in an eco-industrial park. Although this model could never be simply applied to another region, the lessons learned could be used for the alleviation and inspiration for other biofuel production plants worldwide.
- As shown in the text biofuels encompass a large range of material and energy inputs and outputs. Therefore, a linear view of biofuel production should be avoided. In its stead, biofuel production systems should be viewed from a wider systems perspective to account for by-products and all material and energy flows.

9.2 Benefits to the Field of Industrial Symbiosis Using the Application of Biofuels

The application of biofuels also provides many new concepts and ideas for industrial symbiosis. These ideas can be outlined as follows:

- More details related to individual exchanges is required in the field of industrial symbiosis. The classification method produced outlines a method to include details about how the exchanges originate and are destined, which can add more resolution to how synergies are viewed by respective actors.
- As Chertow and Christensen state, the geographic proximity of industrial symbiosis could be expanded to allow for “virtual” exchanges. In the biofuel industry these are everyday practices. However, limits to industrial symbiosis may not account for the world markets that biofuel production currently uses for raw materials and selling of by-products. If these are considered, a larger-virtual industrial symbiosis can be uncovered.
- A new concept for the industrial symbiosis field is that of the upcycling tenant. As described, biofuel production, i.e. biodiesel and biogas, can be used as upcyclers of difficult to dispose of wastes. By converting wastes into valuable energy carriers in addition to the sought after by-products, biofuel production plants can offer many industries a means to upgrade their wastes. Inclusion of such a tenant may therefore attract other industries. The upcycling tenant may also see the possibility for co-location w/ other firms for easy access to raw materials.
- Industrial symbiosis literature may also benefit from the addition of yet more examples of renewable energy in symbiotic activities which could open for a number of the questions outlined in the subsequent section, *Further Research*.
- Finally, biofuels may be used directly for synergies. As this is not a common occurrence in the literature, products may be used for exchanges similar to wastes and by-products.

9.3 Further Research

Based on the previous research, many interesting paths have been produced for future research. Much of the literature available for industrial symbiosis presumes that industrial symbiosis results in environmental and economical improvements (Chertow & Lombardi, 2005; Jacobsen, 2006; Karlsson & Wolf, 2008). The next phase of this research project is to quantify environmental performance and energy efficiency improvements from the many current and potential synergies provided. However, interesting questions also exist, which may be answered with more qualitative data, some of which has been provided as part of this research project. These interesting questions for future research include:

- What are the economic outcomes of synergies?
- Are there any restrictions for the implementation of these synergies?
- What is needed for these synergies to be implemented?
- What synergies are “best” from an environmental perspective?
- Which synergies would lead to a better environmental performance?
- How should synergies be prioritized?
- Are by-product synergies more beneficial than utility synergies?
- Under what distances are by-product and material exchanges considered sustainable in the biofuel production industry?
- Would industrial symbiosis activities be different if bioenergy was used in place of fossil energy? How could the symbiotic exchanges differ?

Therefore it is proposed that more research be conducted to answer these questions. This could be done through providing further details using tools such as life cycle analysis and costing, material flow analysis and environmental impacts (Jacobsen, 2006) to aid in showing the true implications of industrial symbiosis for the biofuel industry.

REFERENCES

- Amiri, S., Trygg, L., & Moshfegh, B. (2009). Assessment of the Natural Gas Potential for Heat and Power Generation in the County of Östergötland in Sweden. *Energy Policy*, 37(2), 496-506.
- Angerbauer, C., Siebenhofer, M., Mittelbach, M., & Guebitz, G. M. (2008). Conversion of Sewage Sludge into Lipids by *Lipomyces Starkeyi* for Biodiesel Production. *Bioresource Technology*, 99(8), 3051-3056.
- Baas, L., & Boons, F. (2007). The Introduction and Dissemination of the Industrial Symbiosis Projects in the Rotterdam Harbour and Industry Complex. *International Journal of Environmental Technology and Management*, 7(5-6), 551-577.
- Baas, L. W., & Huisingh, D. (2008). The Synergistic Role of Embeddedness and Capabilities in Industrial Symbiosis: Illustration based upon 12 years of Experiences in the Rotterdam Harbour and Industry Complex. *Progress in Industrial Ecology*, 5(5-6), 399-421.
- Bai, F. W., Anderson, W. A., & Moo-Young, M. (2008). Ethanol Fermentation Technologies from Sugar and Starch Feedstocks. *Biotechnology Advances*, 26(1), 89-105.
- Bernesson, S., Nilsson, D., & Hansson, P. (2004). A Limited LCA Comparing Large- and Small-Scale Production of Rape Methyl Ester (RME) under Swedish Conditions. *Biomass and Bioenergy*, 26(6), 545-559.
- Börjesson, P. (2004). *Energianalys av drivmedel från spannmål och vall (Energy Analysis of Transportation Fuels from Grain and Ley Crops)* IMES/EESS Report No.54. Lund University- Department of Technology and Society.
- Börjesson, P. (2006). *Energibalans för bioetanol-en kunskapsöversikt (Energy Balance of Bioethanol- A Review)* IMES/EESS Report No. 59
- Börjesson, P. (2009). Good or Bad Bioethanol from a Greenhouse Gas Perspective - What Determines This? *Applied Energy*, 86(5), 589-594.
- Börjesson, P., & Mattiasson, B. (2008). Biogas as a Resource-Efficient Vehicle Fuel. *Trends in Biotechnology*, 26(1), 7-13.
- Börjesson, P., & Tufvesson, L. M. (2010). Agricultural Crop-Based Biofuels – Resource Efficiency and Environmental Performance Including Direct Land Use Changes. *Journal of Cleaner Production*, In Press, Corrected Proof.
- Burström, F., & Korhonen, J. (2001). Municipalities and Industrial Ecology: Reconsidering Municipal Environmental Management. *Sustainable Development*, 9, 36-46.
- CECP (2007). *Regional Resource Synergies for Sustainable Development in Heavy Industrial Areas: An Overview of Opportunities and Experiences*. Perth, Australia. Center of Excellence in Cleaner Production (CECP). Curtin University of Technology.

- Chertow, M. R. (2000). Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and the Environment*, 25, 313-337.
- Chertow, M. R. (2007). "Uncovering" Industrial Symbiosis. *Journal of Industrial Ecology*, 11(1), 11-30.
- Chertow, M. R., & Lombardi, D. R. (2005). Quantifying Economic and Environmental Benefits of Co-located Firms. *Environmental Science and Technology*, 39(17), 6535-6541.
- Christensen, T. B., & Kjaer, T. (2009). Industrial Symbiosis in the Energy Sector. *Joint Actions on Climate Change*, Aalborg, Denmark.
- Chung, K., Kim, J., & Lee, K. (2009). Biodiesel Production by Transesterification of Duck Tallow with Methanol on Alkali Catalysts. *Biomass and Bioenergy*, 33(1), 155-158.
- Cleantech Östergötland (2009) The Energy Complex at Händelö. *Cleantech Magazine-Environmental Technology in the Twin Cities of Sweden*, 1, 16-17.
- Danestig, M., Gebremehdin, A., & Karlsson, B. (2007). Stockholm CHP Potential—An Opportunity for CO2 Reductions? *Energy Policy*, 35(9), 4650-4660.
- de Wit, M., Junginger, M., Lensink, S., Londo, M., & Faaij, A. (2010). Competition Between Biofuels: Modeling Technological Learning and Cost Reductions Over Time. *Biomass and Bioenergy*, 34(2), 203-217.
- Demirbas, A. (2009). Progress and Recent Trends in Biodiesel Fuels. *Energy Conversion and Management*, 50(1), 14-34.
- E.ON Värme Sverige (2009). *E.ON i världsunikt energikombinat*.
- Eisenhardt, K. M., & Graebner, M. E. (1989). Building Theories from Case Study Research. *Academy of Management Review*, 14(4), 532-550.
- Frosch, R. A., & Gallopoulos, N. E. (1989). *Scientific American*, 261(3), 144-152.
- Gibbs, D., & Deutz, P. (2007). Reflections on Implementing Industrial Ecology through Eco-Industrial Park Development. *Journal of Cleaner Production*, 15(17), 1683-1695.
- Gnansounou, E., Dauriat, A., Villegas, J., & Panichelli, L. (2009). Life Cycle Assessment of Biofuels: Energy and Greenhouse Gas Balances. *Bioresource Technology*, 100(21), 4919-4930.
- Graedel, T. E. (1996). On the Concept of Industrial Ecology. *Annual Review of Energy and the Environment*, 21(1), 69-98.
- Haas, M. J. (2005). Improving the Economics of Biodiesel Production through the Use of Low Value Lipids as Feedstocks: Vegetable Oil Soapstock. *Fuel Processing Technology*, 86(10), 1087-1096.

Hughes, T. P. (1987). The Evolution of Large Technological Systems. In W. Bijker, T. P. Hughes & T. Pinch (Eds.), *The Social Construction of Technical Systems: New Directions in the Sociology and History of Technology* (pp. 51-82). United States of America: The MIT Press.

Hughes, T. P. (1993). *Networks of Power: Electrification in Western Society, 1880-1930* The John Hopkins University Press.

IEA (2008). *100% Biogas for Urban Transport in Linköping Sweden: Biogas in Buses, Cars and Trains*

International Energy Agency (2005). *Biofuels for Transport- An International Perspective*. Paris, France: International Energy Agency.

Jacobsen, N. B. (2006). Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology*, 10(1-2), 239-255.

Karlsson, M., & Wolf, A. (2008). Using an Optimization Model to Evaluate the Economic Benefits of Industrial Symbiosis in the Forest Industry. *Journal of Cleaner Production*, 16(14), 1536-1544.

Kim, Y., Mosier, N. S., Hendrickson, R., Ezeji, T., Blaschek, H., Dien, B., et al. (2008). Composition of Corn Dry-grind Ethanol By-products: DDGS, Wet cake and Thin Stillage. *Bioresource Technology*, 99(12), 5165-5176.

Korhonen, J., Wihersaari, M., & Savolainen, I. (2001). Industrial Ecosystem in the Finnish Forest Industry: Using the Material and Energy Flow Model of a Forest Ecosystem in a Forest Industry System. *Ecological Economics*, 39(1), 145-161.

Lantmännen Agroetanol AB (2009a). *Lantmännen Agroetanol AB Homepage*. 2009, www.agroetanol.se

Lantmännen Agroetanol AB (2009b). *Produktblad-Agrodrank 90. (in Swedish- Product Sheet- Agrodrank 90 Fodder)*

Lantz, M., Svensson, M., Björnsson, L., & Börjesson, P. (2007). The Prospects for an Expansion of Biogas Systems in Sweden—Incentives, Barriers and Potentials. *Energy Policy*, 35(3), 1830-1843.

Lifset, R., & Graedel, T. E. (2002). *Industrial Ecology: Goals and Definitions*. Cheltenham, U.K.: Edward Elgar.

Lin, C., & Li, R. (2009). Fuel Properties of Biodiesel Produced from the Crude Fish Oil from the Soapstock of Marine Fish. *Fuel Processing Technology*, 90(1), 130-136.

Linköpings kommun (2008). *Biogas i Linköping-från Idé till Verklighet (in Swedish: Biogas in Linköping- From Idea to Reality)*. Linköping, Sweden:

- Ljunggren Söderman, M. (2003). Recovering Energy from Waste in Sweden—A Systems Engineering Study. *Resources, Conservation and Recycling*, 38(2), 89-121.
- Lowe, E. A. (1997). Creating By-product Resource Exchanges: Strategies for Eco-industrial Parks. *Journal of Cleaner Production*, 5(1-2), 57-65.
- Lowe, E. A. (2001). *Eco-industrial Park Handbook for Asian Developing Countries*. Asian Development Bank:
- Lowe, E. A., & Evans, L. K. (1995). Industrial Ecology and Industrial Ecosystems. *Journal of Cleaner Production*, 3(1-2), 47-53.
- Lowenthal, M. D., & Kastenbergh, W. E. (1998). Industrial Ecology and Energy Systems: A First Step. *Resources, Conservation and Recycling*, 24(1), 51-63.
- 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*,
- Mittelbach, M., & Renschmidt, C. (2004). *Biodiesel- The Comprehensive Handbook*. Graz, Austria: Martin Mittelbach.
- Murphy, J. D., & Power, N. M. (2008). How Can We Improve the Energy Balance of Ethanol Production from Wheat? *Fuel*, 87(10-11), 1799-1806.
- Neves, L., Ribeiro, R., Oliveira, R., & Alves, M. M. (2006). Enhancement of Methane Production from Barley Waste. *Biomass and Bioenergy*, 30(6), 599-603.
- Pokoo-Aikins, G., Heath, A., Mentzer, R. A., Mannan, M. S., Rogers, W. J., & El-Halwagi, M. M. (2010). A Multi-criteria Approach to Screening Alternatives for Converting Sewage Sludge to Biodiesel. *Journal of Loss Prevention in the Process Industries*, In Press, Accepted Manuscript
- Power, N. M., & Murphy, J. D. (2009). Which is the Preferable Transport Fuel on a Greenhouse Gas Basis; Biomethane or Ethanol? *Biomass and Bioenergy*, 33(10), 1403-1412.
- Predojević, Z. J. (2008). The Production of Biodiesel from Waste Frying Oils: A Comparison of Different Purification Steps. *Fuel*, 87(17-18), 3522-3528.
- Robinson, P. H., Karges, K., & Gibson, M. L. (2008). Nutritional Evaluation of Four Co-product Feedstuffs from the Motor Fuel Ethanol Distillation Industry in the Midwestern USA. *Animal Feed Science and Technology*, 146(3-4), 345-352.
- Saunders, J. A., & Rosentrater, K. A. (2009). Survey of US Fuel Ethanol Plants. *Bioresource Technology*, 100(13), 3277-3284.
- Stake, R. E. (1995). *The Art of Case Study Research*. Thousand Oaks, California: Sage Publications, Inc.
- Svensk Biogas AB (2009). *Svensk Biogas AB Homepage*, 2009, www.svenskbiogas.se

Taheripour, F., Hertel, T. W., Tyner, W. E., Beckman, J. F., & Birur, D. K. (2010). Biofuels and Their By-products: Global Economic and Environmental Implications. *Biomass and Bioenergy, In Press, Corrected Proof*

Tekniska Verken i Linköping AB (2010). *Tekniska Verken i Linköping Homepage*, 2009, www.tekniskaverken.se

Van Beers, D., Corder, G., Bossilkov, A., & Van Berkel, R. (2007). Industrial Symbiosis in the Australian Minerals Industry: The Cases of Kwinana and Gladstone. *Journal of Industrial Ecology*, 11(1), 55-72.

van Beers, D., Corder, G. D., Bossilkov, A., & van Berkel, R. (2007). Regional Synergies in the Australian Minerals Industry: Case-studies and Enabling Tools. *Minerals Engineering*, 20(9), 830-841.

Van Berkel, R. (2009). Comparability of Industrial Symbioses. *Journal of Industrial Ecology*, 13(4), 483-486.

Williams, A., & Katz, L. (2001). The Use of Focus Group Methodology in Education: Some Theoretical and Practical Considerations. *International Electronic Journal for Leadership in Learning*, 5

Wolf, A., & Petersson, K. (2007). Industrial Symbiosis in the Swedish Forest Industry. *Progress in Industrial Ecology*, 4(5), 348-362.

Worldwatch Institute. (2006). *Biofuels for transport: Global Potential and Implications for Sustainable Energy and Agriculture*. London; Sterling, VA: Earthscan.

Yang, S., & Feng, N. (2008). A Case Study of Industrial Symbiosis: Nanning Sugar Co., Ltd. in China. *Resources, Conservation and Recycling*, 52(5), 813-820.

Yin, R. K. (1994). *Case Study Research: Design and Methods*. Thousand Oaks, California: Sage Publications, Inc.