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INDUSTRIAL SYMBIOSIS AND BIOFUELS INDUSTRY: BUSINESS VALUE AND ORGANISATIONAL FACTORS WITHIN CASES OF ETHANOL AND BIOGAS PRODUCTION

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THE SWEDISH KNOWLEDGE CENTRE
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PREFACE

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SUMMARY

Industrial symbiosis (IS) involves collaborations among diverse, and predominantly local and regional, actors that create additional economic and environmental value through by-product exchanges, utility and service sharing, and joint innovations. While the importance of IS for the development of biofuels is commonly recognised hypothetically, this study aims at advancing understanding of the actual contribution provided in two real life examples–one focusing on grain-based ethanol production and the other focusing on biogas production in a co-digestion unit. Moreover, this study highlights the importance of organisational factors that help shape, and explain relevant organizational and inter-organizational behaviour relevant for emergence and development of successful symbiotic partnerships – here referred to as “social determinants”.

Studied cases provide clear insights on multiple business and environmental benefits of IS. Reducing input and operational costs, increasing material and energy productivity, creatively improving access to substrate with improved social acceptance, reducing exposure to market volatilities, and providing improved environmental performance–with market differentiation advantages–are among key impacts observed. Moreover, IS strategies are also found to enable creation of new markets, assist the evolution towards more complex bio-refineries, and help with recognising biofuel industry as an integral part of sustainable resource use at a wider societal level.

With regards to organisational determinants of synergistic partnerships, the findings of the study reinforce the importance of organisational proximity, alignment of strategic objectives and organisational cultures, intensity and quality of communication, inter-organisational knowledge exchange and learning, formulation of effective and efficient governance mechanisms, trust building, and level of support from different public governance bodies. While the organisational proximity provided by common ownership and being part of the same organisational field assists synergy development in initial phases, as the parties accumulate relevant capabilities, they are able to move towards more complex and more rewarding partnerships. The findings also emphasise that with dedicated support from governance bodies, particularly at the local and regional levels, development of knowledge-, relational- and mobilisation capacities for IS can be enhanced, and these can catalyse accelerated development of synergistic relations benefiting both the biofuel industry and the wider society.

CONTENTS

1 INTRODUCTION

Transport remains a sector with highest dependence on fossil energy globally (IEA, 2016) and in Sweden (Swedish EPA, 2016). In Sweden the sector was responsible for 84% of country's fossil fuel consumption in 2015 (Swedish EPA, 2016) and with a 34% share was the largest contributor to greenhouse gas emissions. As a country with ambitious goals for reducing climate impacts, Swedish government aims to achieve fossil independence in transport sector by 2030 (SOU, 2013). Although significant progress has been made and Sweden already has a relatively large share of biofuels (accounting for 14.7% of fuel mix in 2015 (Swedish EPA, 2016)) meeting the target requires, among others, significant increase in biofuels use (Swedish EPA, 2016), national production of which would be desirable. However, increased and more-efficient production of biofuels is challenging, among others, due to the difficulties in achieving, and maintaining, economic and environmental efficiency in production. The raw biomass characteristics contribute to these challenges as they make their excessive transport costly and thereby favour shorter supply distances and smaller processing units–thereby limiting the scope for scale economies (Wright and Brown, 2007; Gwehenberger et al., 2007; Gustafsson, et al., 2011). There are also growing concerns about primary resources use, encouraging increased reliance on secondary resources in production. Furthermore, given the dynamic and rapidly changing factors surrounding the biofuel industry, designing the new systems with view of resilience in the long run is an important consideration (Mu et al., 2010). At this point, fostering integration and cooperation with diverse local and regional actors presents a viable strategy for improved environmental (Martin & Eklund, 2012) and economic performance (Gustafsson et al., 2011; Ersson et al., 2015;).

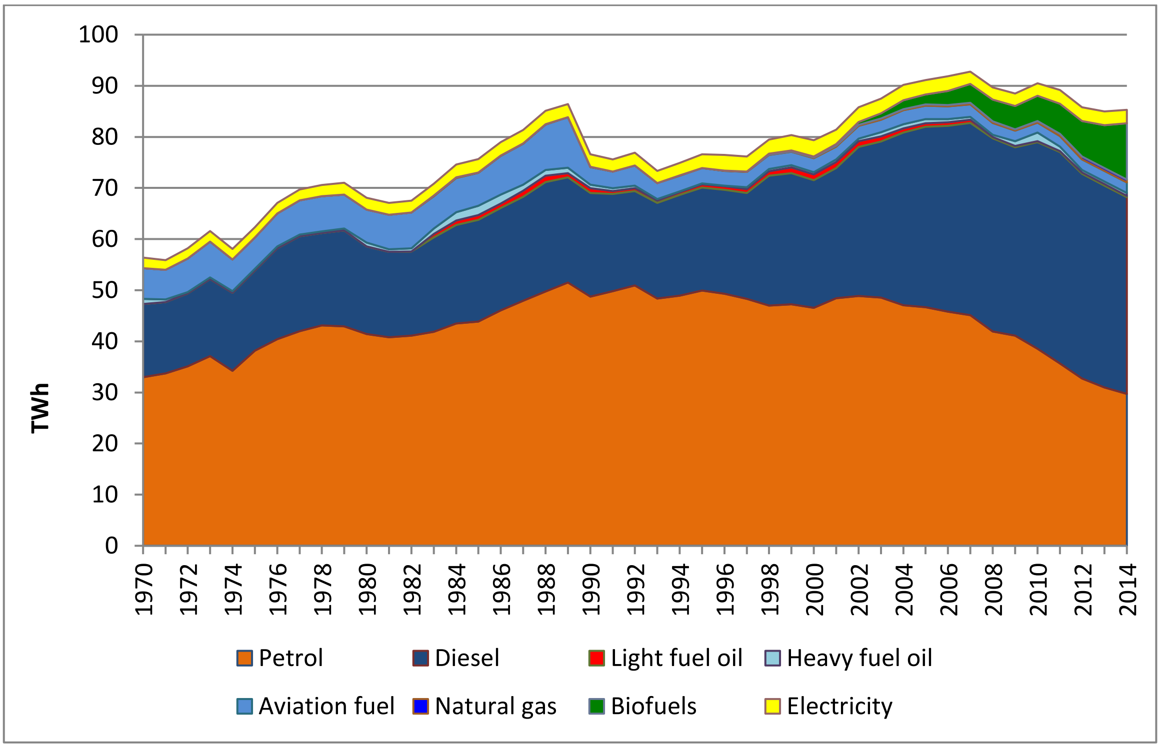

Figure 1. Historic development of energy sources used in transport in Sweden – values in TWh (Based on data from Swedish Energy Agency (2016))

Industrial symbiosis (IS) refers to collaborative approaches to resource management where multiple actors, often from diverse backgrounds, collectively realise solutions whose benefits are beyond what can be achieved by acting alone. As the resulting resource productivity improvements create both environmental and business value, the concept has recognized potential to contribute to the development of more sustainable businesses and economies (European Commission, 2011; The WorldBank, 2012).

Industrial symbiosis holds an important potential to assist the development of more bio-based (Gustafsson et al., 2011), and distributed economies (Ristola and Mirata, 2007). Its importance for the biofuel sector is also recognized both implicitly (e.g. Sassner & Zachi, 2008; Börjesson, 2009; Mu et al., 2011; Ekman et al., 2013; Börjesson et al., 2013;) and explicitly (Martin & Eklund, 2011; Ersson, 2014; Martin, 2013a&b; Gonela & Zhang, 2014) but predominantly hypothetically. Although synergistic relations are generally accepted to benefit the biofuel industry, how, and to which extent, these benefits materialise in real-life cases remains inadequately studied (Martin, 2015 and Peck et al., 2016 are among rare exceptions). Moreover, these studies typically have a static focus, and do not attend to the highly dynamic character of biofuel industries (Ersson et al., 2015).

Moreover, within the field of biofuels, the concept is primarily handled by highlighting technical possibilities and their probable economic and environmental outcomes. Awareness of techno-economic possibilities, although necessary, is seldom sufficient to result in operational synergies in the absence of right organisational conditions and social processes (Howard-Grenville and Boons, 2009) – or what some IS researchers collectively refer to “institutional capacity” (Boons and Spekkink, 2012). These factors are widely studied within industrial symbiosis, and highly related inter-organizational management, research fields, but have received limited attention from biofuel stakeholders. Providing private and public biofuel stakeholders with improved knowledge on these factors, as well as approaches that can affect these in desired directions, can assist identification of development bottlenecks and the formulation strategies that can effectively support accelerated and sustained development of biofuel sector.

This report aims to provide a closer look on the interplay between industrial symbiosis and biofuel developments. By synthesising information from relevant literature with the analyses of selected Swedish cases, the report aims to provide improved understanding regarding:

- the role of industrial symbioses for the emergence and successful development of biofuel industries;
- key organizational and social factors and approaches influencing the successful development of synergistic resource collaborations with high relevance to biofuel industries.

Such understanding can contribute to the formulation of strategies in support of industrial symbioses beneficial for biofuel industries. As such, one of the target group of the report includes private actors engaged with biofuel production as well as others who may develop energy, material or utility synergies with biofuel industries. The other group includes policy makers primarily at local, regional levels that can influence synergistic developments directly or indirectly.

2 METHODS AND LIMITATIONS

Part of this study is based on a literature review focusing on selected challenges to biofuels developments and key features of industrial symbiosis. Findings from these two related streams were synthesised to better emphasise the importance of industrial symbioses for biofuels industry. Here, attention is placed on the diverse ways industrial symbiosis can create business value, as well as the organizational and social dimensions influencing the symbiotic developments.

The empirical part of the study focuses on two operational biofuel systems–one involving grain-based ethanol production and the other concerning biogas fuel production through co-digestion–where industrial symbioses have dynamically played an important role in developments. Information on these cases were gathered through interviews, document analyses and reporting of direct experiences. The impacts of the synergies and their enablers are investigated and analysed qualitatively. Based on the findings, general conclusions are drawn for better utilising IS for biofuel industries.

3 BIOFUELS INDUSTRY AND INDUSTRIAL SYMBIOSIS

3.1 SELECTED CHALLENGES FACING BIOFUEL DEVELOPMENTS

Biofuels are promoted, together with other bio-based products, on the grounds of reducing greenhouse gas emissions, creating alternatives that can offset economic and supply risks linked to fossil fuels, and stimulating industrial and rural development (Langeveld & Sanders, 1012; European Commission, 2012). In order to deliver on these promises, biofuels need to achieve sufficient economic and environmental performance in a socially acceptable fashion. However, they are faced with important challenges concerning economic viability, technical feasibility, and social acceptability (Langeveld and Sanders, 2012). Diverse factors contribute to these challenges, a comprehensive coverage of which is beyond the scope of this study. Some of these, with high relevance to our discussion, include the following.

Unlike fossil counterparts, which only need to be mined, biomass needs to be produced and therefore require extra resource input. Biomass resources also lack spatial and exergetic concentration (Östergård et al., 2012) and can be intermittently available. These features intensify transport and storage needs. The heterogeneous composition, on the other hand, not only requires extra treatment (of both feedstock and intermediates) during production but also results in the generation rather large amounts of by-products–the management of which may further increase transport and logistic needs[1]. Moreover, in order to maintain the ecological integrity of the production base, recycling of nutrients from production back to land is desirable (Gwehenberger et al., 2007). As a consequence collection, transfer, storage and processing of bio-resources, as well as handling of certain by-products, are energy intensive and costly. Furthermore, scale economies[2]–a highly effective cost reduction strategy greatly benefiting fossil-based production units (Shoesmith, 1988; Wright and Brown, 2007)–have limited applicability in biofuel systems. As enlarging production units also requires a larger collection (and distribution) radius, part of the benefits of scaling up production are eroded by increased transport costs (Gwehenberger et al., 2007). Raw biomass resources are also typically controlled by a larger number of actors, with diverging interests regarding how to handle their assets. This situation brings further logistical and administrative challenges (Ersson, 2014) and can further increase the so-called transaction costs.

Relatedly, biofuels are more expensive to produce than fossil fuels and their development remain dependent on subsidies, long-term sustainment of which can be problematic (Peck et al, 2016). These dynamics also have implications on the environmental and social performance of the products. Depending on characteristics of the overall production system the environmental impact of biofuels can vary greatly within a life-cycle view, with some systems providing limited or no environmental gains (Börjesson, 2009). Use of food- or energy-crops give rise to additional concerns

[1] Such as in the case of applying digestate from biogas in agricultural land.

[2] Scale economies, or "economies of scale" refers to the cost advantage that arises with increased output of a product in larger production units. It arises due the inverse relationship between the quantity produced and per-unit fixed costs and due to reduced variable costs per unit because of operational efficiencies (Investepodia, 2017).

over displacing human and animal nutrition products and creating negative climate impacts via indirect land use changes (Ponton, 2009; Yarris, 2011). Consequently, regulatory requirements are placed on producers with the intention of securing sustainability of biofuels (European Union, 2009). Given the relatively recent developments of markets rewarding CO_2 performance with a price premium (e.g. Germany), environmental performance is moving beyond securing a "license to market" and starting to carry higher strategic importance. Although more abundant than cultivated biomass, forest biomass is also a limited resource facing competing applications. Consequently, efficient utilization of this feedstock is also critical (Lönnqvist et al., 2016).

An additional challenge facing the bio-based products, including biofuels, is related to the creation of markets (Hellsmark et al., 2016). This is particularly challenging for those biofuels that cannot fit within the existing technical regime (such as drop-in) fuels but instead require an alternative regime characterised by their special demands on distribution and use, or both (Peck et al., 2016).

It is also important to note that, as compared to fossil-based counterparts, biofuels industry is in earlier stages of its development with significant potential for further development and is strongly influenced by multiple dynamic domains all displaying constant change and uncertainty, such as commodity markets, political landscape, production technologies, other related industries and sectors, as well as natural systems. As Mu and collaborators (2011) argue, in order to acquire, maintain, and improve viability (or resilience) in such a complex and dynamic business ecosystem, players of the sector need to aim beyond sole efficiency optimisation and need to pursue strategies that will provide *diversity*, *adaptability* and *cohesion*. When optimisation approaches are used, the resulting plants are based on strict assumptions and require a narrow range of conditions and scales for successful operation. Such rigid systems are unlikely to provide such qualities. Development approaches that consider diversity, adaptability and coherence, on the other hand, are likely to result in more robust designs, characterised by: making integrated use of different technologies; being flexible to use multiple feedstock streams and valorise by-products into multiple products; being mutually symbiotic with a variety of industrial sectors; and being environmentally efficient and readily scalable (Mu et al., 2010). Developing systems with such qualities poses a range of new challenges, a detailed review of which is beyond the scope of this study. What is of particular interest here is the fact development and maintenance of inter-organizational and inter-sectoral collaborations–that is, with actors that are outside traditional organisational fields of biofuel producers– is of key importance for the viability of the biofuel businesses. To be successful with such synergistic relationships, need to develop certain organisational resources and capabilities and social capital, including networks, shared norms and social trust that can contribute to mutually beneficial outcomes.

3.2 BACKGROUND TO INDUSTRIAL SYMBIOSIS

Industrial symbiosis is a central element of the overarching industrial ecology field, which aims to reduce the ecological impact of industrial activities (Boons et al., 2016), among others, by creating connections among industrial actors where someone's waste can be turned into someone else's input (Frosh & Gallapogous, 1989). The concept, however, lacks a common definition and diverse definitions have differing implications in terms of included actors, resources and relations; geographic system boundaries; expected outcomes, and; the dynamic nature of the concept (Chertow, 2000; Lifset and Graedel, 2001; Mirata and Emtairah, 2005; Boons et al., 2011; Lombardi and Laybourn, 2012). In her most widely cited definition Chertow (2000) refers to industrial symbiosis as engaging "*traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity*." This definition clarifies some of the important mechanisms of the concept, but is short on others, such as synergies based on intellectual and organisational resources and their innovation implications. The emphasis on "competitive benefits" also implies that businesses are the sole actors to benefit from symbiotic transactions. The importance of geographic proximity, although valid in many cases, is not universally applicable either. Departing from their practical experience and prioritising the innovative and change-oriented dimension of the concept, Lombardi and Laybourn (2012) propose that industrial symbiosis should be seen as engaging "*diverse organizations in a network to foster eco- innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes."* This definition is closely aligned with our understanding of the concept, although we acknowledge that the boundaries of symbiotic relationships not necessarily need to span a network of organisations, and can be limited to only two.

Although the term "industrial symbiosis" spontaneously triggers a perception of the concept being exclusively focused on manufacturing industry, the word "industrial" should be understood in an all-encompassing manner referring to diverse activities of industrial societies. Such an understanding qualifies other activities–e.g. agriculture, forestry, fisheries–and organizations–e.g. communities, governance bodies, cities and knowledge organizations–as important entities to be a part of symbiotic relations. Of these, cities are of particular interest given their concentrated and growing resource needs and waste generation problems (UNEP, 2016). Consequently, contemporary scoping and application of industrial symbiosis encompasses a richer set of economic activities and organizations and the term "industrial and urban symbiosis" is sometimes used (van Berkel et al., 2009; Murdel, 2016). Having worked with the concept both as researchers and practitioners in international and in Swedish settings, members of the industrial symbiosis research team in Linköping University also emphasise the key importance of involving urban systems in symbiotic partnerships. Relatedly, this group prefers to use "industrial and urban symbiosis" term and defines it as "a set of collaborative processes where actors of diverse backgrounds collectively identify and develop innovative resource management solutions. Such solutions are recognised to create business (e.g. Paquin et al., 2015; Chertow and Lombardi, 2005) environmental (e.g. van Berkel et al., 2009; Schwarz & Steininger, 1997) and development value (Zhu and Ruth, 2014). The mechanisms by which these are achieved can be diverse, but the most commonly recognized ones include the following:

- **By-product synergies**–involve Improved utilization of non-product outputs that arise from one facility (and that may be traditionally discarded or wasted) as productive inputs in another facility to replace another production input.
- **Utility synergies**–involves pooled use and shared management of commonly used resources, or handling of flows, such as steam, compressed air, electricity, water and wastewater;
- **Service synergies**–involves shared provision of services by a third party for other needs – such as waste management, or logistics;

- **Supply synergies–** where actors co-locate with their main supplier(s)/customer(s), or collaborate with them in other ways, in order to reduce transport needs and provide/receive stable and good quality inputs.

These synergies can be created among processes or facilities owned by the same organisation; among actors co-located in an industrial park (in times also having a common management structure), or can be among actors virtually spread in a region (Chertow, 2000).

Another mechanism, that is relatively under-emphasised but certainly not less important, is related to learning and innovation outcomes of IS. More specifically, IS is recognized for its potential to facilitate and enable collective development and mobilization of intellectual and social capital through joint learning (Boons et al., 2016) resulting in **improved innovation capabilities** (Mirata & Emtairah, 2005). According to Mirata and Emtairah (2005) IS contributes to innovation by offering collective problem definitions, enabling search and discovery at inter-sectoral interfaces, and by learning through inter-organizational collaboration. Collaborating actors in symbiotic relations can combine unique but complementary knowledge and capabilities, resulting in new ideas and improved mobilization capabilities for the development and deployment of new products and services with superior environmental performance. As such, IS can also be seen as a potential starting point for broader collaborations on sustainable development (Posch, 2010). These knowledge and capability synergies–with higher similarities to conventional business alliances–may also be less dependent on physical proximity among actors, although proximity may offer advantages (Hansen, 2013). Despite these strengths, the development of successful industrial symbiosis networks contingent on a complex set of inter-connected factors–as elaborated further below–and are found to develop only in contexts where the right conditions prevail.

These mechanisms can provide environmental value by reducing primary resource use in production and transportation, and by reducing emissions and waste generation. They can also create business value in multiple ways, including: reducing costs for material and energy input, waste management and emission control (Chertow and Lombardi, 2005; Jacobsen, 2006; van Berkel et al., 2009) and for transport and logistics; increasing the share of marketable products and associated revenues (Paquin et al., 2015); improving the value of traditional products (Ersson, et al., 2015); reducing volatility risks in product (Bell, 2015) and input markets; increasing supply security (Ersson, et al., 2015); reducing or eliminating needs for capital investments (Rehn, 2013); removing bottlenecks to business growth (Angren et al., 2012; Sülau, 2016), and; improving organizational eco-innovation capabilities that result in new products and services (Mirata & Emtairah, 2005; Lombardi & Laybourn, 2012). As these benefits are not constrained to businesses but also extend to wider set of societal actors, IS is considered to hold an important potential to contribute to regional sustainable development in general (Mirata, 2005; Ristola & Mirata, 2007; Zhu and Ruth, 2014).

The potential of industrial symbiosis to contribute to environmental and economic performance is manifested by international (Chertow and Lombardi, 2005; Jacobsen 2006; Van Berkel et al. 2009; Paquin et al., 2015) and Swedish (e.g. Mirata, 2005; Wolf, 2007; Hackl & Harvey, 2010) examples. The concept's importance for supporting the development of more bio-based and distributed economies is also emphasised both explicitly (Ristola and Mirata, 2007; Gustafsson et al., 2011) and implicitly (e.g. Ekman et al., 2013; Börjesson *et al*., 2013; Östergård et al., 2012). A relatively large number of IS networks, with varying degrees of maturity and complexity, are already operational in

Sweden[3]. Some of these also clearly manifest the concept's relevance and importance of more bio-based developments.

3.3 BIOFUELS INDUSTRY AND INDUSTRIAL SYMBIOSIS

In order to deliver expected contributions, biofuels production needs to be technically feasible, economically viable, and socially and environmentally acceptable. To this end, improving resource efficiency and overall economic and environmental performance through industrial symbiosis approaches is widely recognized–implicitly or explicitly–as a viable strategy (Börjesson, 2009; Kayleen et al, 2010; Huang et al., 2010; Mu et al., 2011; Martin & Eklund, 2011; Börjesson et al., 2013; Ekman et al., 2013; Ersson, et al., 2015). The importance of industrial symbiosis for biofuel systems amplifies with the recognition that confining (at least part of) the biofuel value chains within local/regional boundaries offer better resource efficiency and improved maintenance of the productive soil capacity. This, however, also limits the economic benefits that can be derived from large-scale plants (Gwehenberger et al., 2007) and magnifies the importance of "economies of scope"–that is, producing two or more distinct goods from the same production facility, at a cost that is lower than producing each separately.

By developing synergistic relations with other relevant local/regional actors biofuel industry can reduce feedstock, energy, transport and utility costs (Lönnqvist et al., 2016; Wetterlund, 2013), can creatively increase the availability of inputs (Huang et al., 2010; Raghu et al., 2012). It can also gain access to feedstock and energy with higher environmental performance (Börjesson et al., 2013; Martin & Eklund, 2011) and better social acceptance (Gustafsson et al., 2011; Langeveld and Sanders, 2012). Moreover, overall material and energy productivity of production can be enhanced by turning by-products of production into productive inputs for other activities providing business (Pierick et al., 2012; Odegard et al., 2012) and environmental benefits (Börjesson, 2009). These relations can be confined biofuel actors–for example, by using by-products of ethanol and bio-diesel production as substrate for biogas production, or substituting fossil methanol in bio-diesel production (Martin et al., 2012)–or can be among the actors that are part of the same value chain of a particular material – for example pulp and paper or saw mills can be integrated with thermo-chemical processes for fuel production (Börjesson et al., 2013). However, given the organic-based nature of the industry, a broader range of synergies can also be developed with external industries and actors. For example, sourcing biomass from residual flows of agriculture, industries, forestry, and from communities may increase feedstock availability, reduce costs, improve environmental performance and improve social acceptance for biofuel industry (Gustafsson et al., 2011). By-products of biofuel industry, on the other hand, can be turned into valuable inputs for the food, feed, chemicals and materials industries, as well as for agriculture (Gustafsson et al., 2011; Langeveld and Sanders, 2012). From a resilience point of view, production units compatible with residues and capable of valorising by-products will be more favourable (Mu *et al*., 2011). Utility and service partnerships with other actors may provide access to low-cost and/or low-carbon energy and may reduce resource demands of different life-cycle stages (Martin and Eklund, 2011).

[3] Further information about selected industrial symbiosis can be found from the on-line portal developed by Linköping University (http://industriellekologi.se) and the authors can be contacted for further information.

The locally/regionally oriented characteristics of both biofuel systems and IS can also offer further strengths. Bosman and Rotmans (2016) argue that two of these are linked to the following: First, regional level may provide particular strengths for cross-sectoral collaboration assisting both the identification of, and experimentation with, innovations that can catalyse progress. Second, regional level initiatives can be better protected from the potential threat posed by the established regime (Bosman and Rotmans, 2016)

A large spectrum of industrial symbiosis potentials is technically applicable to biofuel industry. A study by Linköping University (2012) identified more than 110 distinct potential by-product and utility synergies, based on extensive literature review and expert consultations (Martin et al., 2012). Tables 1 and 2 provide an overview of the number and scope of identified synergies. More information about identified options can be found in Appendix A[4].

Table 1. By-product and utility synergies applicable to biofuel industry. (Based on Martin et al., 2012.)

Scope of Synergies	By-Product Synergies		Utility Synergies	
	Number	Example	Number	Example
Biofuel→Biofuel	*26*	*Ethanol stillage as substrate for biogas* *CO2 from ethanol production used for methanol production*	*4*	*Shared odor control equipment between ethanol & biogas plants* *Use of ethanol waste heat in bio-diesel production*
Biofuel→External	*46*	*CO2 from ethanol production used in beverage production* *Biogas digestate used as solid fuel*	*6*	*Residual heat from ethanol, bio-gas, biodiesel used to heat greenhouses*
External→Biofuel	*30*	*Bioethanol from food industry residues* *HVO from slaughterhouse waste*	*1*	*Heat from power production used for ethanol distillation or biogas upgrading*
Total	***102***		***11***	

Table 2. Industries that can develop synergies with biofuel industry. (Based on Martin et al., 2012.)

Industry	Number of Synergies
Food/Feed	24
Energy/Fuel	12
Chemical/Cosmetics	9
Municipal	9
Agriculture	8
Materials/Building	6
Algae	4
Environmental Services	4
Greenhouse	4
Forestry/Paper	3
Total	***83***

Selected benefits linked to these symbioses have also been quantified based on hypothetical (e.g. Sassner & Zachi, 2008; Börjesson, 2009; Börjesson et al., 2013) and actual (e.g. Martin, 2015) cases. Based on a number of Swedish case studies of forest-based biofuel production projects at different development stages in Sweden, Peck and collaborators reinforced the key importance of

[4] Some additional by-product synergy options, with different levels of technical maturity, was later identified by Martin (2013) and is available among the f3 publications.

synergistic relations for the overall development of the sector and concluded that *"the pursuit of cross industry and multi-faceted synergies will improve the strength of an initiative – and may be crucial to success."* (Peck *et al*., 2016, p. 98).

Clearly, benefits are not limited to biofuel actors; others including farmers, industries, and communities can also benefit from their synergistic integration with biofuel industries by increasing revenues, reducing costs and creating new development opportunities (Mu *et al*., 2011; Gustafsson, 2011). Biofuel industries' integration with such actors would also help address wider societal problems related to waste generation, resource use and depletion. Therefore, through such integration the biofuel system can be recognized as an important piece of the "sustainable resource use" puzzle rather than being solely concerned with the problem of "sustainable energy for transport".

Mutual benefits can also be obtained by developing material, energy and knowledge synergies between the biofuel industry and fossil based fuel and chemicals industries–seen as the main competitors. One of the manifestations of this was observed within the iconic industrial symbiosis network located in Kalundborg, where one of Europe's first straw-based ethanol plants became operational, supported by its synergistic connections, among others, with a petroleum refinery (See figure 1 below) and a coal-fired power plant. Operational synergies between bio- and fossil-fuel actors have also been demonstrated in Sweden, and are acknowledge to have critical importance for all involved actors (Peck et al., 2016). Hypothetical studies also highlight considerable benefits to both sectors from improved integration (Hackl & Harvey, 2010).

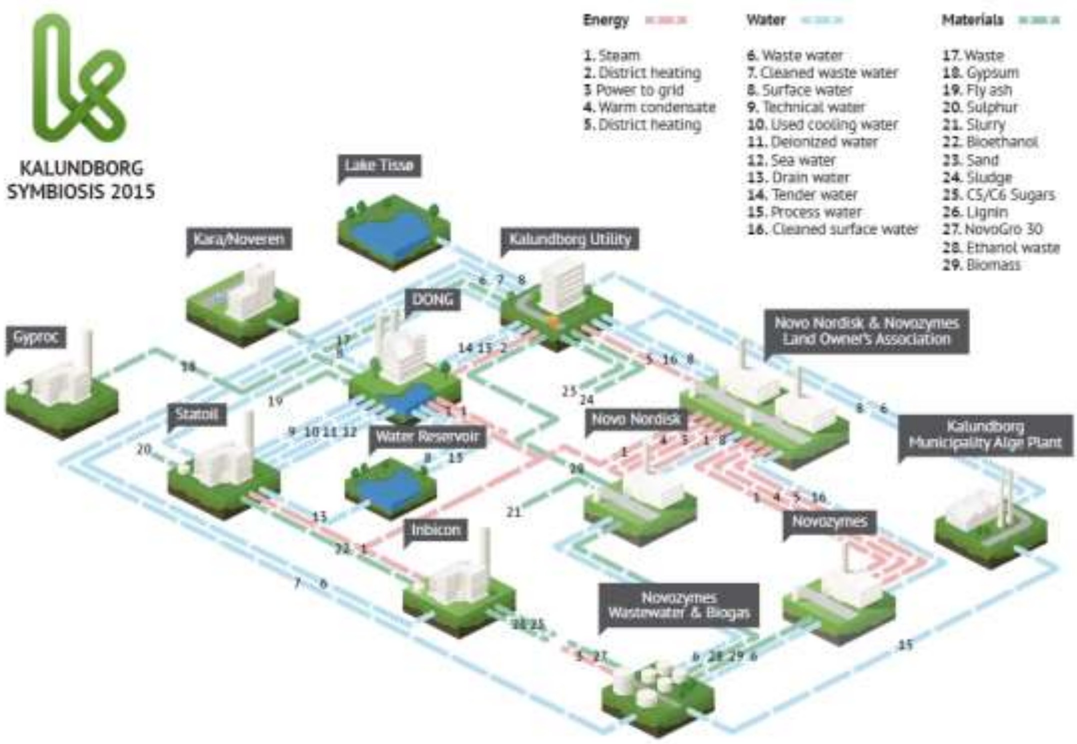

Figure 2. Within the famous industrial symbiosis network in Kalundborg, a second generation bioethanol plant, Inbicon, was developed in a synergistically integrated fashion, among others, with Statoil refinery. (Source: www.symbiosis.dk.)

Recognition of technical possibilities for material and energy exchanges, and other kinds of synergies, certainly offers a step in the right direction. However, the ability of taking advantage of these in practice requires successfully navigating through organizational, social and institutional challenges facing their realization. These are elaborated on in the coming section.

3.4 KEY FACTORS INFLUENCING THE EMERGENCE AND DEVELOPMENT OF INDUSTRIAL SYMBIOSES

Industrial symbiosis, and highly related inter-organizational collaboration, research fields also provide knowledge and insights on the diverse set of inter-related factors influencing the emergence and development of symbiotic relations. At a generic level, these factors are related to "techno-economic" aspects and "social mechanisms".

Technically, certain synergies requires the existence of certain industrial activities, with compatible resource needs and supplies, within the same regional industrial system[5]. Moreover, compatibility between the quantitative, qualitative, and temporal characteristics of resource supply and demand by compatible actors is an important consideration, particularly given the fact that some of the flows that form the basis of exchanges are generated without considering further use, and may show high fluctuations (Mirata, 2004; Gibbs & Deutz 2007). Presence of actors with relatively large and stable material and energy in- and out-puts (the so called physical anchors) is therefore considered to offer a key strength (e.g. Chertow, 2000). Geographic proximity is recognized for its techno-economic implications (Chertow, 2000). Proximity can be indispensible for utility and service sharing–particularly for flows that are either not possible or too costly to transfer over long distances. As material flows that are involved in synergistic linkages typically have lower value, close distances between generators and users enhance their valorisation chances. For by-products having higher inherent value or higher waste treatment costs proximity may have lower importance (Jenssen et al., 2011). Therefore, while proximity brings advantages, it is not a strict necessity for the development of synergies (Boons et al., 2016; Chertow and Ehrenfeld, 2012; Velenturf and Jensen, 2016). The extent of required processing and associated resource demands (Côté & Cohen-Rosenthal, 1998); availability and accessibility of appropriate and cost-efficient processing and logistics infrastructure (Mirata, 2004; van Beers et al. 2007); as well as specificity of technology investments required for resource exchanges are other important technical determinants. Diversity of actors, and consequently of in- and out-puts, processes and technologies, are argued to enrich the opportunities for resource collaboration (Chertow, 2000) and may provide improved technical robustness (Korhonen, 2005).

Expectedly, investment requirements and economic return expectations of synergistic possibilities, as well as their ranking against other investment options play a significant role (Chertow, 2000; Mirata, 2004; Yap and Devlin, 2016). However, for IS cases these are influenced by different dynamics and can be more complex to assess with high certainty. For example, secondary-resources

[5] It should be noted that the mix of industries operating in a regional economic system can change dynamically, creating more supportive conditions for symbiotic relationships or acting otherwise. The development of the industrial mix can also be influenced to create better conditions for industrial symbioses.

having inherently low-value, and type and extent of processing needed for the valorisation may result in longer payback times[6] (Mirata, 2005; Fichtner et al., 2005). Current situation and future outlook (and uncertainties) regarding the prices of virgin commodities, value of secondary resources, stability of markets for revalorized by-products, costs of alternative handling options, and associated transaction costs can negatively influence cost-benefit outcomes and their reliability. This problem can be amplified in cases where these factors have a high dependence on policies whose future developments are unclear. Moreover, in certain novel applications practical benchmarks can be scarce and techno-economic performance knowledge can only be established in an experiential fashion. These complexities do not only affect choices of the parties that are potential parties in symbiotic relations, but may also have a significant bearing on the availability and cost of financing required (Sakr et al., 2011).

The presence of technically and economically feasible options is certainly important for industrial symbiosis. However, as manifested by empirical examples, both the identification and assessment of such opportunities (Boons and Spekkink, 2012) and their implementation (Gibbs and Deutz, 2005 & 2007; Jacobsen, 2007) are dependent on various organisational and institutional factors (Howard-Grenville & Boons, 2009). Therefore, strong emphasis is given to such organisational and institutional factors that help shape, and explain, organizational and inter-organizational behaviour relevant for emergence and development of industrial symbiosis (Ashton, 2008; Jacobsen, 2007; Doménech and Davies, 2009; Howard-Grenville and Paquin, 2008).

At the institutional level, government policies at different levels and relevant regulatory framework are widely recognized for their central role in influencing incentives in secondary resource use and other inter-organisational resource collaboration (Mirata, 2004; Gibbs & Deutz, 2007; Costa et al., 2010; Lehtoranta et al., 2011; Boons et al., 2011; Boons & Spekkink, 2012). Initiatives by government bodies for matching and coordinating industrial activity is also regarded key (e.g. von Malmberg, 2004; Mirata, 2005; Boons and Spekkink, 2012). Historical trajectories of industrial interactions within a country or region (Mirata, 2004), the contribution of key stakeholders to organizational decision making, and financial and economic pressures that affect the valuation of organisations' actions (Howard-Grenville & Paquin, 2008) and the types of economic coordination supported by the institutional context (Spekkink, 2015) are other important institutional determinants.

For individual organizations, the level of strategic importance given to industrial symbiosis is dependent on awareness of applicable opportunities and motivations to pursue them. Identification of symbiotic opportunities requires the actors to identify complementary resources or needs of others and evaluate the value of combining these with their own resources or needs (Dyer and Singh, 1998). These may need to be compounded with technical and operational information regarding new applications (Mirata, 2004). As for most conventional organisations IS opportunities may lie outside of what is considered core business (Deutz & Gibbs, 2008), organisations may not allocate the necessary resources, and may lack relevant routines, for their systemic identification. Moreover, information required from organisations may be considered sensitive (Mirata, 2004; Gibbs and Deutz, 2005), and its disclosure will require motivation and trust from involved parties (Doménech & Davies, 2009; Boons and Spekkink, 2012). In addition to accessing information, parties also

[6] This can be exacerbated when the positive environmental effects provided by synergies are not properly valued in the markets.

need to have what is called “absorptive capacity” in order to recognize the value of obtained information for new opportunities (Dyer and Singh, 1998).

Identified opportunities need to have a strong enough alignment with the strategic objectives of the organizations. In addition to the economic considerations mentioned earlier, (actual or perceived) implications of synergistic exchanges on human resources, product quality and acceptability, and organisational image may become other critical factors (Yap and Devlin, 2016). Furthermore, as the symbiotic partnerships differ from traditional market transactions, their implementation often requires customised business models. In addition, industrial symbiosis often entails new dependencies, the extent of which is influenced, among others, by the importance of the exchanged resource, the discretion over its allocation and use, and the extent of available alternatives (Walls and Paquin, 2015). In times, such dependencies are coupled with investments in relation-specific assets (e.g. physical, site-specific or human-resource assets). Therefore, proper handling of power imbalances (Fichtner, 2005; CECP, 2007; Walls & Paquin, 2015) and/or perceived risks against opportunistic behaviour (Dyer & Singh, 1998) is critical–not only for the initiation but also for the future development of synergistic partnerships. Moreover, once a partnership is started, its development and expansion greatly depends, among others, the intensity and quality of knowledge exchange among involved parties and their learning outcomes (Dyer and Singh, 1998). These demarcations emphasise the importance of governance mechanisms employed. To support the emergence and development of IS, such mechanisms need to effectively incentivise collaboration and knowledge exchange while at the same time providing solid safeguards against opportunistic behaviour. Moreover, as their design and implementation entails costs, governance mechanisms also need to be efficient (Dyer and Singh, 1998).

Linked to the above, **trust** is seen central to IS developments due to its key influence for the willingness of actors to share information, to do business together, and to commit to cooperation and synergistic relations (Gibbs, 2003; Ashton, 2008). The presence and strength of formal and informal ties among relevant actors (Jacobsen, 2007; Howard-Grenville and Paquin, 2008) and the level of communication these enable are therefore critical for building up trust (Hewes and Lyons, 2008; Domenéch and Davies, 2011; Yap and Devlin, 2016). IS being a predominantly cross-sectoral phenomena can cause challenges to this end as actors expected to collaborate are likely to belong to different organisational fields[7] and therefore may lack not only the communication channels and past experience in working together (Gustafsson et al., 2011) but also common norms and worldviews (Howard-Grenville & Paquin, 2008). In order to cooperate, actors are first required to cross into each-others’ fields, and possibly create new fields, and develop new communications and interactions, shared objectives, and trusting relations among a new set of members (Howard-Grenville & Paquin, 2008). Such cross-fertilisation may enrich the diversity in world-views, values and interests (Korhonen, 2005), as well as in knowledge and organizational capacities that can support innovation (Boons and Berends, 2001; Mirata & Emtairah, 2005). However, this may also be a resource intensive and slow process (Boons and Baas, 1997). IS being a dominantly local/regional phenomena, on the other hand, offers strengths as physical proximity can increase the likelihood of

[7] According to Howard-Grenville and Paquin (2008) “a field is a community of organizations that partakes of a common meaning system and whose participants interact more frequently and fatefully with one another than with actors outside of the field. In contrast to an industry, a field may include regulators, pressure groups, communities, and/or businesses engaged in quite different activities.”

encounters and reduce communication costs, thereby stimulating the emergence of trustful relations through repeated exchanges, the possibility of observation and a loss of anonymity. A potential lack of physical proximity will need to be compensated by cognitive, organizational and institutional proximity (Hansen, 2013). Additional organizational factors, such as local authority for relevant decisions (Baas and Boons 2004), and experiences in past relationships (Mirata, 2004; Ashton 2008) also have an influence on the emergence and development of synergies.

Boons and Spekkink (2012) place diverse organizational and social factors under the umbrella they refer to as "institutional capacity for IS" and argue that the following sub-elements play a key role in shaping the set of options relevant actors consider feasible for action:

> **Relational capacity** includes a network of relationships that increases mutual understanding and trust among parties and serves to reduce transaction costs among firms. Increased relational capacity enables actors to consider a wider range of options by making the risky transactions–that would be too costly in the absence of strong personal and professional relationships and mutual trust–more viable.
>
> **Knowledge capacity** involves the ability to acquire and use timely and relevant information about feasible symbiotic linkages. The advancement of the knowledge capacity can enlarge the opportunity set of actors when feasible options that were previously unnoticed become recognised. It can also make the opportunity set smaller if the information acts as a reality check on previously over ambitious expectations.
>
> **Mobilization capacity** refers to the ability to activate relevant firms and other parties to develop symbiotic linkages. Its advancement enables to target and involve the actors that are necessary for symbiotic exchanges, to influence policies and regulations that are relevant to these exchanges, and to attract external resources that may be necessary to realize the exchanges.

It is relevant to note that similar social factors are also recognized for their key development influence within the Technological Innovation System (TIS) work for bio-refinery developments (Hellsmark et al., 2016)–where biofuels are a part. For example, TIS studies also recognise social capital–and its building blocks such as trust, mutual dependence, and shared norms–as critical enablers (Hellsmark et al., 2016). However, while the TIS work on bio-refineries primarily focuses on a relatively homogenous organizational field (e.g. actors that can be part of technology platforms for cellulosic feedstock, developers of these technologies, and woody biomass value chain actors), industrial symbiosis targets actors with diverse sectorial backgrounds, with different organizational belongings[8].

IS research also emphasises the importance of facilitation efforts by coordinators, or other suitable intermediaries, that can favourably influence relevant development determinants (e.g. Boons and Baas, 1997; Mirata, 204; Boons and Spekkink, 2012). Recognized ways by which intermediaries

[8] On the other hand, TIS work and frameworks will recognise a wider set of actors as relevant. Relevance of such diverse actors are also acknowledged in industrial symbiosis literature generically, and elaborated on specifically for focused synergistic development cases.

can support IS developments include the following:

- generating awareness and encouraging engagement;
- acting as a connecting hub for improved communication, interaction and build-up of trust;
- facilitating the formation of a shared vision and objectives;
- brokering information, relationships, or knowledge;
- offering specialized knowledge, administrative capabilities and physical assets;
- reducing transaction costs and implementation-gap times;
- securing access to external resources (e.g. finance, technology, policy);
- performing collection, storage, intermediate processing, and blending of material streams;
- assisting the formulation of suitable business models and governance mechanisms;
- legitimising the emerging relationships/networks and acting as a bridge between private and public sector, and;
- enabling deeper reflective learning[9].

Municipalities, regional authorities, business associations, non-governmental organisations, research and knowledge institutions, utility and waste management companies, and specialised consultants are recognised suitable parties to serve as intermediaries. Of these, municipalities and other local and regional public bodies appear particularly well-positioned to support IS developments (Burström and Korhonen, 2001; von Malmborg 2004 & 2005). In the Swedish context, operational examples also indicate that municipal bodies and reginal authorities are particularly well-positioned entities to support IS developments. These parties are considered credible and impartial, and often have ready access to relevant economic actors as well as some of relevant knowledge resources (e.g. selected in- and out-puts, energy demands, process parks). They are also in charge of relevant planning and permitting processes. Depending on the level of their integration and cooperation, these different functions can indirectly assist or hinder development of synergies. Last, but not least, business and economic development, provision of quality utility services, and protection of environment are among core mandates of these organisations. Therefore, such local and regional administration bodies can take the lead and, if necessary in cooperation with businesses and academic partners, create communication and interaction platforms, collect and share relevant information, and help develop the assisting plans and processes thereby supporting the development of industrial symbioses.

[9] List compiled from Mirata (2004), Mirata and Emtairah (2005), Jiao and Boons (2014), Doménech and Davies, (2011), Ashton (2008), Ashton and Bain (2012), Behera, et al. (2012), Boons and Spekkink (2012), Chertow and Ehrenfeldt (2012), Paquin & Howard-Grenville (2012), Panyathanakun et al. (2013), and Walls and Paquin (2015.)

4 CASES DEMONSTRATING THE INTERPLAY BETWEEN INDUSTRIAL SYMBIOSIS AND BIOFUEL INDUSTRIES

4.1 ETHANOL PRODUCTION IN LANTMÄNNEN AGROETANOL

Agroetanol is Sweden's only large-scale grain-based fuel ethanol producer. It is fully owned and operated by the Swedish Agricultural Cooperative, Lantmännen. Their plant's production started at a smaller capacity in 2001. In selecting a site for the plant, the island of Händelö just outside Norrköping was considered among the suitable candidates due to good access to multi-modal transport, its vicinity to agricultural land, and closeness of grain and fuel storage infrastructure. However, the final decision to locate in Händelö was primarily motivated by the possibility to source process steam from the neighbouring CHP plant, owned and operated by E.ON. In 2009 AE increased its production capacity fourfold, during which time E.ON made a parallel investment into a new boiler to meet increasing process steam demand. As part of this expansion the plant's energy efficiency was improved. After the steam is used, the hot condensate is returned back to E.ON and is used in the DH networks serving local communities. Up until 2015, the ethanol produced was primarily used in the Swedish market as low (E5) and high (E95) blends with gasoline. However, in 2015 80% of the production was exported, and a high blend with diesel (ED95) was introduced in the Swedish market.

Stillage, a protein-rich organic stream, is an important by-product of ethanol production as it arises in large volumes and has good potential for producing various value-added products. Since its early days, Agroetanol processed stillage and produced fodder products (Dried Distillers Grain with Solubles (DDGS) and some liquid products), which was sold to the fodder industry or directly to farmers. However, initially the plant lacked sufficient capacity to process all the stillage and therefore a part of it was sold to the neighbouring biogas plant to be used in the production of fuel-grade biogas. As part of the plant's expansion in 2009, by-product processing capacity was enhanced. With its current configuration, Agroetanol can process approximately 600 000 t/y of cereal grain and produce 230 000 m^3/y (around 1 342 GWh and approximately 12% of biofuels used in Sweden in 2014) of ethanol and 200 000 t/y of fodder. As the use of thin stillage for biogas production presented an economically sub-optimal solution for both parties, the transaction was terminated by the end of 2012. However, a small fraction of organic by-products, which cannot be valorised internally, are still sent to the plant in Linköping (see next case) and used for biogas production.

High-purity carbon dioxide (CO_2) arising from the fermentation step is another important by-product from ethanol production. In late 2014/early 2015, in partnership with the industrial gas company AGA, a new plant co-owned by Agroetanol came into operation with a production capacity of 100 000 t/y of CO_2. The plant benefits from the high concentration of the CO_2, purifies and converts the gas to liquid carbonic acid (Lantmännen, 2015). The resulting product is sold in the growing industrial and domestic CO_2 market, creating further value for the company as a biogenic and domestically produced product with improved supply security.

In order to improve grain feedstock characteristics, EA cooperates with the plant breeding division in their corporate group to develop a special ethanol wheat type with higher starch content and overall yield, but lower protein content. This new type requires less fertilisers and therefore can offer gains both to the farmers and AE, while also reducing overall greenhouse gas emissions. However, until now the new wheat type has not been largely accepted, due to unsuccessful dissemination in the sales organisation and among the farmers (Ersson et al., 2015).

Up until 2015, more than 99% of production was based on cereal grains, majority of which is sourced from the Swedish market. In 2015, the plant started to use starch-rich food industry residues (e.g. baked products) as substrate. Although the total quantity of such stream is small–as compared to overall grain usage–such practice helps substitute part of the grain used for production.

In 2015, the company also started producing ED95–a high blend-in ethanol fuel compatible with specialised engine platforms, a world-leading producer of which is Swedish vehicle manufacturer, Scania. As a downstream oriented value-chain collaboration, the company started a collaboration platform called Etha together with Scania. The aim of this initiative is to offer a complete system solution–including biofuel production, vehicle technology, and distribution–for customers who are interested in sustainable transport solutions with secure supply and good environmental performance (Agroetanol, 2016). The company also has research and development partnerships with academia, where new bio-chemical processes that can enhance the ethanol yield and fodder properties, as well as the production of food, are investigated. Agroetanol's synergistic relations that were operational as of 2017 are schematically depicted in Figure 3.

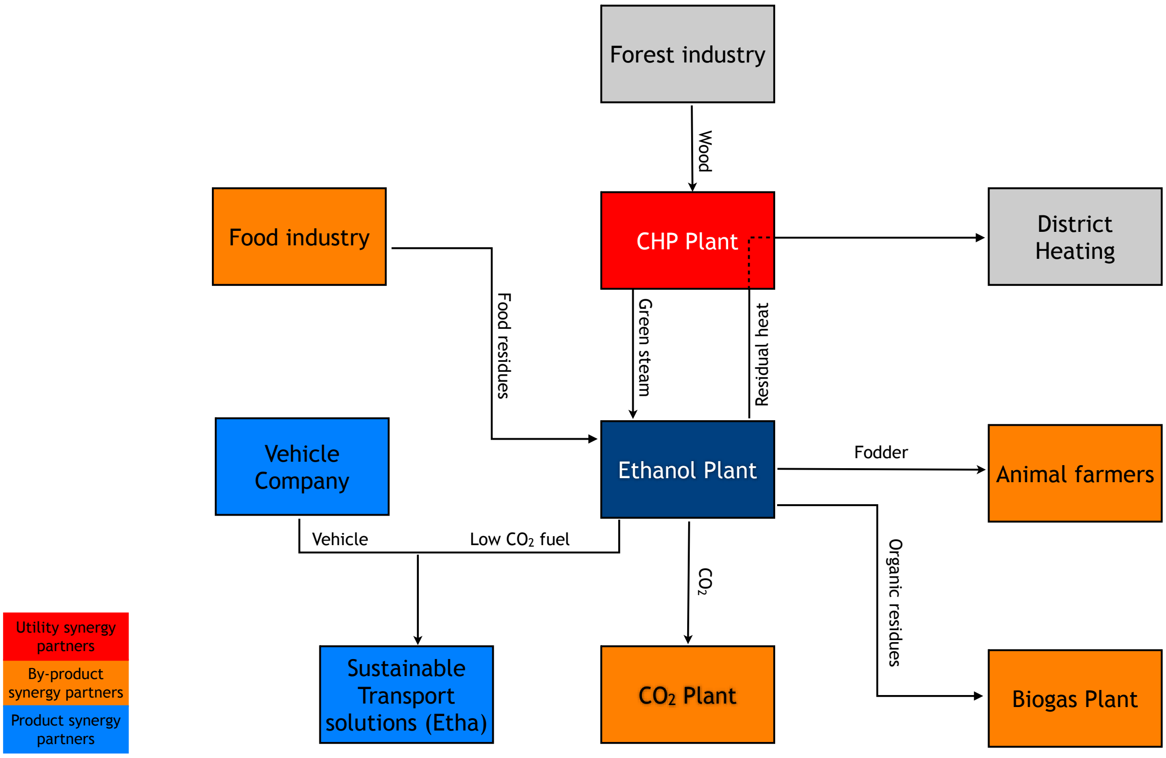

Figure 3. Schematic depiction of main synergistic relations of Agroetanol (Note: not a process lfow diagram.)

The company is working on a diverse range of additional areas related to producing new value-adding products and using alternative inputs. Examples of these include: development of chemical feedstock for bio-plastics production, growing of protein rich edible fungi for food and feed applications from organic by-products (currently under demonstration scale), and use of cellulosic feedstock in production (van Schantz, 2017).

4.2 BIOGAS PRODUCTION IN LINKÖPING

In Linköping, use of biogas as a transportation fuel started at a small scale in early 1990s, motivated by a demand to reduce transport-induced air pollution at the city center. By then, upgraded biogas from local wastewater treatment plant – owned and operated by the municipally owned utility company Tekniska Verken (TV)–fuelled five of the public transport busses. Larger scale production started in 1997, motivated by continued demand for alternative fuels in public transport and the need of finding a sustainable management option for problematic waste streams from local industries. The original company, Linköping Biogas AB, was set up with a joint ownership of TV, local slaughterhouse and farmers association, LRF. Based primarily on slaughterhouse waste, gas produced in the new plant was sufficient to fuel 30-40 busses in the city, and resulting digestate was sold as fertiliser to local farmers.

In early 2000s, with waste trucks and private cars also running on biogas, the market was expanding. To respond to and further stimulate this expansion, it was desirable to build more filing stations and develop a gas grid. Other partners considered the required investments too high, and the developing business too far from their core, and thus in 2004 Svensk Biogas AB–a fully owned subsidiary of Tekniska Verken (TV) AB–became the sole owner of the biogas operations. The slaughterhouse and LRF remained as long-term suppliers and customers. The substrate base is gradually expanded to include waste from food processing industry, with two different streams sourced from a local dairy being of particular interest. A partnership was also developed with a local company specialising in sustainable solutions between urban and rural systems (Biototal) for improved marketing of the digestate as fertilizer.

The expansion of the biogas market and the enlarged biogas production capacity in Sweden intensified competition for high quality substrate from slaughterhouses and food industry. Hence, the plant increased its capacity in 2012 with the intention to use organic household waste as substrate, for which a gate-fee can be collected. The biogas plant collaborates with the waste management department of TV for the efficient collection of organic household waste[10].

Around the time of the expansion in 2012, the district heating network of Linköping city was extended to the plant, providing access to high-temperature (~ 90 °C) heat from the nearby CHP plant, which is fuelled by sorted household and industrial waste. Among others, access to high-temperature district heating enabled the company to change its gas upgrading system from water based scrubbing to a new amine based chemical scrubber. In addition to the raw gas produced in the co-digestion reactors (approximately 17 Million Nm^3/y or 102 GWh), the gas produced at the adjacent wastewater treatment plant (approximately 2.9 M Nm^3/y or 18 GWh[11]) has also started to be refined in this new chemical scrubber.

The company also has long-term partnerships with the regional public transport company, Östgötatrafiken, and with Biototal AB, a company specialising in bridging resource flows between urban settings and agricultural systems. Biototal has been helping the biogas company with finding

[10] Organic waste is placed in a green colored bag by the generators, which are collected with other waste fractions and brought to the waste management site. Here the green bags are optically sorted and sent to biogas plant for processing.

[11] Collectively, these two streams correspond to around 1% of biofuels used in Sweden in 2014).

markets for the digestate in the agricultural activities. In 2014, the biogas and digestate production was split and became a part of TV, and Svensk Biogas AB became solely responsible for sales and distribution.

As of 2016 the plant is one of the largest co-digestion plants in Sweden and uses diverse inputs from multiple sources. Out of the total of 120 000 tonnes of substrate processed every year, just below half was household waste. While 15-20% of the household waste comes from Linköping, the remainder is sourced from 15 other municipalities including Norrköping, Katrineholm, Eskilstuna and Västervik, after transporting the material between 43 to 150 kilometers. The remaining substrate is sourced from slaughterhouses, farmers, and residues from food processing and biofuels industries. Although the share of slaughterhouse waste has decreased to about 25% of the total, this is still an important partnership and accounts for about 30% of gas production. Synergistic relations benefiting the biogas production unit in Linköping are schematically depicted in Figure 4.

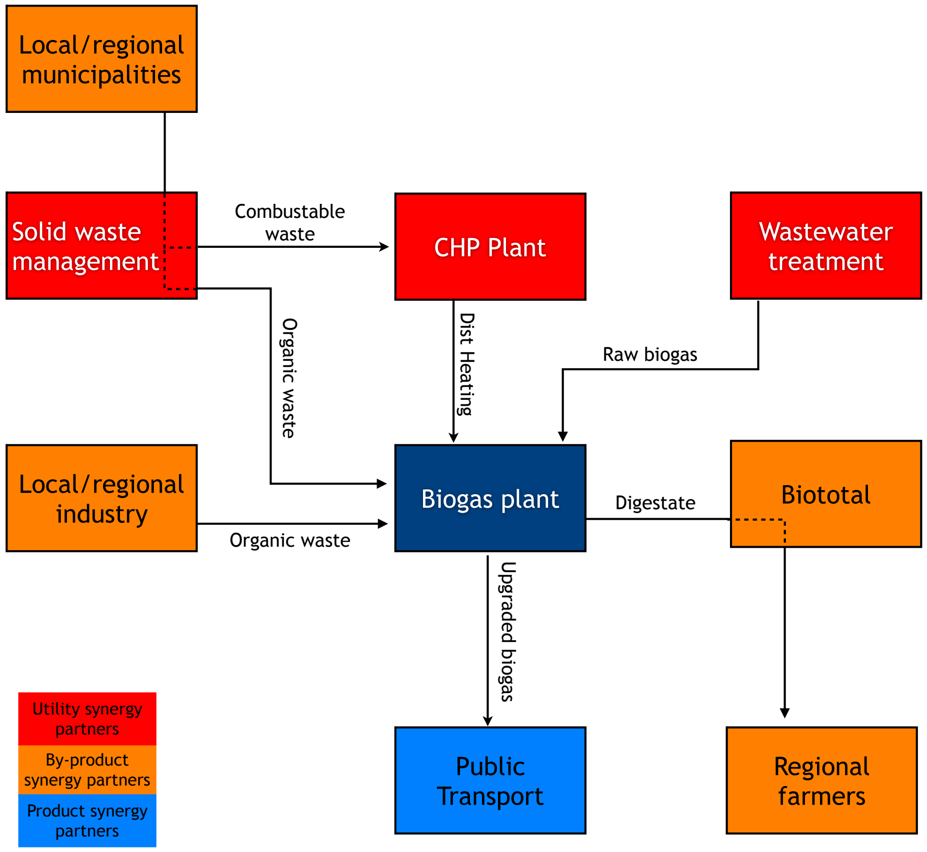

Figure 4. Main synergistic relations benefiting biogas production in Linköping (Note: Not a flow diagram.)

5 ANALYSES

In assessing the implications of symbiotic relations in investigated cases, we focus on three inter-linked aspects: the impacts of selected by-product-, utility-, and supply-synergies on business performance; important organisational, and to a limited extent institutional, factors that affect their development, and; the role of the symbiotic relations in the overall development of players and the sector.

For Agroetanol, the utility synergy of sourcing steam from E.ON has significant value due to inter-related economic and environmental gains. The company was able to avoid substantial capital investments and is freed from responsibilities and costs of operating its own steam system. The steam is priced more competitively as compared to the cost of self-production Moreover, as the price is set on a yearly basis–taking into consideration a set of parameters–it shows smaller variations over time as compared to price fluctuations in fossil fuels. This provides a more stable and predictable business environment for the company and reduces risks. Having steam operations outsourced also enables the company to put more of its resources on core activities. Moreover, since 2009, the company is also able to sell its residual energy to be used for district heating network (Ersson et al., 2015), further reducing its energy costs. The renewable process energy (heat plus electricity) also plays an important role in securing a high environmental performance for the ethanol produced (Börjesson, 2009; Martin & Eklund, 2011). This places the company in a strong position to meet the regulatory requirements for improved CO_2 performance (European Union, 2009) and has become a competitive differentiation enabler. Provision of high-pressure steam by the power plant also enables higher process efficiency in ethanol production.

Within Lantmännen group, Agroetanol is one of the most susceptible companies to market volatilities (Lantmännen, 2013) because both grains (corresponding to more than 70% of production costs) and ethanol (delivering more than two thirds of revenues) are commodities with high price fluctuation. In this regard, synergies allowing valorisation of by-products represent an important business leverage, and resilience strategy. Therefore, the company has dedicated significant resources to increase the amount of protein-rich organic by-products processed into innovative, higher-value-adding fodder products. These efforts were strongly assisted by the fact that the company has access to key knowledge about fodder and fodder markets internally from the Lantmännen group. The corporate connections also give the possibility for direct supply, decreasing costs within the supply chain for some customers. Mainly due to higher protein prices in the global markets and partly due to the higher quality that gives a price advantage over competitors, the income generated from DDGS sales has gradually increased for Agroetanol. While also generating additional income, this reduces company's exposure to high volatility in ethanol markets. Fodder production also increases the environmental performance of the produced ethanol. and can be argued to help avoid potentially costly waste management obligations[12].

Valorisation of previously wasted by-product CO_2 is another important step towards product diversification. Similar to the fodder products, marketable carbonic acid increases company's revenues

[12] In the absence of fodder production, organic residues need to be sent for biogas production or incineration. While the former can generate some value, the latter would be a costly route, particularly given the high water content of the organic residues.

and helps reduce exposure to price volatilities. It also pushes the environmental performance of the key product to the next level of improvement.

The by-product synergies of the company are not limited to its own outputs; important advantages are also enabled by the use of food-industry waste as input, substituting cereal grains. Waste derived substrate is both less costly for the company and its cost shows smaller variations. In addition, it provides access to a feedstock which has better environmental performance and which is less susceptible to social concerns. For this transaction, initially the company was once again advantaged by its connections within the Lantmännen group. However, in time it accumulated relevant technical and organizational assets and started to create operational synergies with other parties. Although the amounts used today are rather small (< 10%), the company is interested in, and working on, increasing the share of substrate derived from suitable by-product streams of food industry.

As stated, synergistic relations provide sizeable environmental benefits, which in the case of Agroetanol recently started to provide important market benefits. The type of energy used in ethanol production is one of the key determinants of the environmental performance of the product (Börjesson, 2009) As the steam provided by E.ON has low CO_2 emissions, so does the produced ethanol. The CO_2 performance is further improved by the production of fodder, the capture and sales of CO_2 released during production, and by substituting industrial food waste for grain. Consequently, the biofuel produced by Agroetanol has superior greenhouse gas reduction performance, offering in excess of 90% reductions (depending on the method of calculation). Up until 2015, company's products were primarily sold for low-blending to the Swedish market, where environmental performance is not rewarded. However, since 2015 majority of the produced ethanol is sold to the German market at a premium, where a premium can be captured incentives to pay for environmental performance are in place based on CO_2 performance (Agroetanol, 2016).

There are also wider societal environmental and social benefits connected to the company´s synergistic relations. For example, as the fodder produced by AE corresponds to around one third of Sweden's protein imports (Agroetanol, 2013), wider environmental gains are enabled by the substitution of imported soya meal. Farmers, that utilize the bio-sludge from Agroetanol as fertilizer, on the other hand, are not only able to reduce their fertilizer costs but also gain access to fertilizers suitable for organic agriculture

While also increasing material productivity, the by-product valorisation is also valuable due to the relationships, competencies, and knowledge it helps to develop. Partnership with Svensk biogas plant in Norrköping was one such example, where the two companies worked together in optimising gas production from a substrate that had problematic characteristics from the perspective of biogas production. Although the transaction was discontinued, both companies consider the experiences and knowledge gained important. For the case of Agroetanol, there is a recognition that the company may need to move towards increased reliance on substrate with less nutritional value–e.g cellulosic materials–in which case, biogas production from residuals will serve as an alternative with high strategic value.

Agroetanol's collaboration with Scania within the Etha platform, on the other hand, represents a unique and vitally important synergistic relationship that enables the creation of niche markets through downstream collaboration on system solutions. By joining complementary resources, the companies are able to move beyond sub-elements–a green truck or a green fuel–and offer a more complete green transport solution. By engaging customers who are interested in such solutions on a long-term basis and by making necessary investments into the enabling infrastructure, the actors are also able to create niche markets for mutually desirable new solutions. This is also a clear example of how partnerships with market incumbents can help the development of relatively new biofuel players. The importance of such synergies between old and new players was already highlighted for biofuel production and upstream processes (Peck et al., 2016). The example with Etha (see Figure 2), however, demonstrates that such partnerships also play an important role downstream from production, for the creation of innovative market spaces. The partners of the Etha platform have a strong interest to further grow the initiative by engaging additional customers interested in developing sustainable transport operations (Etha, 2017).

A range of organisational and social factors has influenced the emergence and development of Agroetanol's synergistic relations. For example, their partnership with E.ON carries strategic importance for all counter-parts. In the case of E.ON, ability to supply steam year round allows the CHP plant to better utilise its production capacity and allow it to produce more green electricity. The plant is also able to process more household and industrial waste (used as fuel) in summer months, where the demand for district heating is low. Moreover, in order to meet Agroetanol's increasing process energy need after its expansion, E.ON has made a parallel investment and installed a new boiler. This allowed the company to extend its district heating network to the town of Söderköping, which is 10 km away –providing more business for the company, and more sustainable heating to Söderköping. AGA, on the other hand, is able to reduce supply security risks and gains access to a green product. For Scania, ability to secure stable access to fuels with superior environmental performance is a key condition to succeed in their strategy of offering low-carbon transport solutions to their customers. For all cases, open communication and trusting cooperation between the companies, and their ability to develop business models that allow linking together industrial processes plays a key role. All synergy partners, including Agroetanol, were able and willing to make the necessary investments, partly due to the fact that the governance mechanisms employed have long time-frames and help provide sufficient incentives and safeguards against opportunistic behaviour. Interesting to note that in some of the cases, such inter-firm governance mechanisms include a hybrid of third-party and self-enforcing mechanisms, such as joint investments and co-ownership. By working together and maintaining a close communication the companies are refining and improving terms of the governance mechanisms that enforce the partnership. Moreover, repeated and open interaction among collaborating parties provide valuable learning to all involved parties and help them identify new collaboration areas and new business development potentials, thereby further strengthening the partnerships. It is also important to note that for some of Agroetanol's synergistic partnerships, and most notably with Scania in Etha platform, the communication and interaction opportunities provided by external collaboration enhancing parties such as Svebio and f3 played an important role, as these allow the parties to get to know and understand each other better, to identify and value their complementary resource endowments, and to develop a trusting relationship. In the case of Agroetanol, a number of additional partnership opportunities are under consideration and was supported by initiatives that bring multiple actors together and enable a communication platform.

For Agroetanol, the ability to access resources available with the corporate group has also been of critical importance, as this helped reduce sensitivities with information sharing and so-called transaction costs. For example, in a scenario where access to fodder and fodder market related competencies and connections within the group was not possible, generic fodder production would still be relatively straight-forward (as the DDGS market is fairly well established) but development and marketing of more specialised alternatives, and their lower-cost delivery, would have required strategic partnerships; the development of which would have required diverse range of extra resources. In other cases, such as the utilisation of suitable food industry wastes substrate, such internally initiated synergistic relations have also enabled the company to develop relevant technical and organisational capabilities, which then paved the road to develop partnerships with external actors. However, it also needs to be noted that some other interesting opportunities – such as farmers using the new grain types better suited for ethanol production – did not develop as desired. A clear understanding of this dynamic requires further inquiry, but it is likely that (lack of) alignment of strategic objectives among involved actors (farmers, seed marketing department of the corporate group, and Agroetanol) is an important factor.

Biogas production in Linköping, on the other hand, was born based on the premises of industrial symbiosis. However, the evolution of the biogas plant and its operational dynamics represent another good example of how the dynamic developments have influenced the sector and how effective responses were developed through increased diversity, flexibility and integration. With the growing demand on by-product streams that are particularly attractive for biogas production, the company experienced a shift towards increased costs and shorter-term contracts for its preferred substrate streams. The company responded to this challenge by expanding its production capacity and diversifying its substrate base. From a technical point of view, this required a parallel shift from having high-specificity in production–optimized for a narrow range of substrate characteristics[13] –to a more flexible system with low-specificity that is capable of handling diverse substrate streams[14].

It is also interesting to note that the economic benefits of substantial scale increase in the biogas plant remains limited. This can be attributed to several factors. Within the new dynamic, changed substrate characteristics reduced the overall production efficiency (although the new cocktail of inputs also reduced the need for micro-nutrient addition). Transport and processing needs for the substrate increased and more digestate has to be handled for every unit of gas produced. The transaction costs are also increased due to increased number of substrate providers and increased digestate volumes requiring management. Despite these seemingly negative developments, the company was able to maintain, and even improve, its economic viability. The synergistic relations that allow inter-connected benefits of improved efficiency and increased access to substrate with a gate fee play an important role in this.

In this context, symbiotic integration with other local utility functions, all owned and operated by the TV, offer important advantages to the biogas plant. For example, the ability to access high-temperature district heating all year round increases productivity and reduces costs. The amount of marketable gas production increases partly due to eliminating the need for internal use of the gas

[13] In the case of Linköping, this required addition of selected micro-nutrients to optimize the digestion of slaughterhouse wastes which was rich in nitrogen.
[14] In the current setting the need for micro-nutrients addition is eliminated.

(for hygienisation and for reactors) and partly due to reduced methane slip in the chemical scrubbing the company is able to employ[15]. This technology also lowers the electricity demand of the plant. The biogas produced in the neighbouring wastewater treatment plant is also transferred to this chemical scrubbing plant for upgrading, which provides additional gains. Last, but certainly not least, the biogas plant's integration with the remainder of solid waste management services of the city allows efficient access to pre-sorted organic household.

The biogas operations receive additional advantages through administrative synergies enabled by improved coordination among diverse utility functions. For example, despite the fact that a larger part of the substrate is sourced from more distant sources, and the substrate provision is governed by shorter-term contracts across the board, the partnership with local actors–and primarily with the slaughterhouse– is of primary importance (due to high yield potential and low transport demand). The company is able to secure longer-term contracts with such local partners because TV is able to offer a "one stop shop" option to companies with diverse utility needs (heat, electricity, water, wastewater, waste), managed collectively by a single account manager. This allows for the development of contracts that benefit both the customer and TV, and provides the biogas operations with more stable access to substrate[16]. Such dynamics are also starting to expand to waste management services offered to other municipalities. That is, TV can offer more complete waste management services (covering a wider set of waste fractions) to the municipalities, and at a competitive rate, which increases the access to organic household waste.

Digestate management is another aspect of biogas production with significant bearing on the viability of operations, and may be a source of entry barrier for new biogas plants. In the case of operations in Linköping, productive management of digestate–by using this by-product as fertilizer and soil-enhancer in agricultural land– has significant economic implications and limits the production scale[17]. In this respect, the collaboration with Biototal, who has complementary resources, is of vital importance. Biototal is a company with solid understanding of agricultural practices and with connections to wider set of farmers. The company has a good knowledge of the needs of farming and farmers, and what it takes to place the digestate on land. It is also well-positioned to understand, establish, and communicate the market value of the digestate–which it sees as a product rather than a waste. While also being good at marketing it, Biototal can provide important feedback regarding the characteristics that can improve the quality and marketability of the digestate. TV, on the other hand, has strong absorptive capacity for such valuable feedback and can use its sound understanding and expertise regarding biogas production to respond to the demands for improved digestate quality. TV was able to engage with substrate providing partners and stimulate changes that improved digestate management dynamics.

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[15] Chemical scrubbing process requires high thermal energy for the regeneration of the scrubbing solvent. For conventional operation 130 °C is required for solvent regeneration. However, in Linköping regeneration is performed under vacuum and therefore 90 °C is sufficient.

[16] The contract durations for biogas substrate transactions secured through such collective approach can be twice as long as compared to other contracts where an integrated offer is not possible.

[17] Larger digestate quantities require finding land application potentials further away and transporting the material over larger distances–both contributing to the cost of operations.

Another important partnership that underpins the success of biogas production in Linköping is the one with regional public transport company, Östgötatrafiken. This company has, since the beginning of biogas production, been consistently committed to using biogas in its fleet and made considerable investments to this end. These were, in turn, matched by the biogas producer who made parallel investments in distribution infrastructure, including a distribution pipeline that assures timely and reliable availability of the fuel.

From an organizational and social perspective it is important to note that, technical and administrative synergies benefiting the biogas operations are supported by the fact that multiple utility functions are under the common ownership of a single parent company–Tekniska Verken. This makes the communication, coordination and governance of symbiotic relations easier and less costly. In a similar fashion, the critical long-term partnership with Östgötatrafiken is enabled and supported by a joint priority given to the use of biogas as a transport fuel and having the governance mechanisms that allow partners to make specific investments. It is, however, also important to note that both TV and Östgötatrafiken are politically influenced entities, with strong alignment towards common political objectives at local and regional levels. Such organisational synergies could be challenging to replicate for other biogas operators where different utility services are under separate ownerships, where the benefits of working together may be more difficult to detect, and where the development of partnerships will entail higher transaction costs.

A different dynamic can be observed in the company's symbiotic relations with other actors that are completely separate and autonomous–such as Biototal or other municipalities, from where organic household waste is sourced. These relations are governed by shorter-term contracts and in times been less stable. Despite interruptions, the partnership with Biototal has nevertheless been evolving successfully, among others, due to strong alignment of values among both companies, open and frequent communication, a clear understanding of respective competencies and their complementarities, continual joint learning with valuable innovation outputs, and governance structures giving incentives for long-term commitment to the partnership. Collective development of mutually beneficial solutions have also played an important role for the biogas plant to securing improved access to substrate from other municipalities.

Expectedly, cases reviewed here have been influenced by policies at different levels. For example, the EU Renewable Energy Directive (EU RES, 2009) and Swedish tax exemptions coupled to RED (see, e.g., Ahlgren, 2012) have provided a key motivation for the emergence and development of the biofuel businesses in the first place. Parts of these policy elements have also provided significant incentives for choices regarding raw materials, by-product management and other issues. However, macro level policy influences are not limited to RED or other biofuel related policies. For example, the Swedish CO_2 taxation as well as other policies such as green certificates have been instrumental in guiding the development of the combined heat and power plant in Norrköping towards the use of greener fuels. Policies concerning the municipal food waste, on the other hand, has stimulated the availability of municipal organic waste for biogas production. Other national initiatives providing investment support to local initiatives with positive climate impact (most notably Local Investment Program (LIP) and Climate investment program (Klimatinvesteringsprogram – KLIMP)) have also been important policy influences. Local and regional policies have also been influential. For example, in the case of biogas developments, municipal policies for reducing air pollution in city centers, both in Linköping and Norrköping, were key in creating early demand for biogas as a transport fuel. The political decision of the Östergötland county administration, taken in agreement with the municipalities of the county, requiring the use of renewable fuels (such as biogas) in public transportation and public sector fleets has also provided important leverages. Development of the Agroetanol plant in Norrköping was also supported during site planning and development by municipal initiatives (Rehn, 2013).

It needs to be acknowledged that while the political landscape presented elements supporting the development of the synergistic relations, the identification of symbiotic opportunities and their realisation was primarily driven within the bounds of intellectual and relational resources of the individual actors, as well as the mobilisation capacity they could generate. It is clear that such self-organizing approach has been successful in creating operational synergistic relations. However, it is also important to note that both Agroetanol and the biogas plant have greatly benefited from the organisational proximity provided by being a part of Lantmännen and TV groups, respectively. These actors have a continual interest in developing additional synergies, which require them to expand their organisational fields. More systemic support from third parties–such as municipalities, universities or business associations–can provide valuable assistance for the development of such additional synergistic relations. This can be supported, among others, by creating communication and interaction platforms that will engage relevant parties in guided discussions and assist the build-up of both relational- and knowledge-capacity. Further work with systemic data collection and analyses can further promote awareness of applicable synergistic partnership opportunities. Last, but not least, a systemic assessment of implementation barriers, and formulation of diverse support interventions will further symbiotic developments through enhancing mobilisation capacity.

6 CONCLUDING DISCUSSION

Further development of biofuels is desirable, however this faces important challenges linked to feedstock access, inadequately developed supply-chain and distribution infrastructure, uncertain environmental performance, price parity with the well-established petroleum industry, as well as inadequate political support (Langeveld et al., 2012; Peck et al., 2016; Hellsmark et al., 2016). Addressing these challenges requires multi-disciplinary action at different levels, some of which are beyond immediate direct control of the biofuel players. However, there are also options available to the actors of the sector that can improve technical and economic efficiency and access to new and existing markets–all of which contribute to the viable development of the sector. One of these approaches involves the development of mutually beneficial synergistic relationships with actors within and outside biofuels sector – or to benefit from industrial symbioses. These benefits can be realised through by-product synergies (i.e. utilising residual flows from other activities as feedstock instead of primary resources and/or turning more of the by-products of biofuel productin into marketable products), utility-synergies (i.e. collaborating with other actors in sharing infrastructure needed for utilities such as steam, compressed air, water and wastewater treatment), service synergies (i.e. shared sourcing of third party service providers, for example, for waste management or logistics), and supply-synergies (i.e co-locating and/or collaborating with main supplier(s)/ customer(s) in a way to improve feedstock quality and reduce costs). Some of the common problems that the biofuel industry faces, and how these could be addressed by different synergistic relations are summarised in **Fel! Hittar inte referenskälla.**.

Table 3. Selected contributions of industrial symbiosis to address development challenges in biofuel industry.

Selected challenge facing biofuel industry	Support possibly provided by industrial symbiosis
Feedstock availability	Sourcing feedstock from residual streams creatively increases availability
High feedstock costs	Cheaper or negative-cost feedstock from residual streams
High feedstock logistics costs	Service sharing among feedstock users reduce individual costs
High volatility in input markets	Residual-derived inputs offer better price stability
Environmental performance of feedstock	Feedstock derived from residual streams have better environmental performance
Social acceptability of feedstock	Feedstock derived from residuals have better social acceptance
Feedstock quality	Supply synergies allow access to higher-quality substrate Diversification of by-product use provides a better cocktail (for biogas production)
High energy demand	Lowered energy needs with use/valorisation of residual flows and/or utility sharing
High energy costs	Use of residual energy or energy utility sharing reduces costs
Environmental quality of energy source	Energy with higher environmental performance from residuals or shared utilities
High by-product generation	Value creation from by-products Reduced costs for by-product handling
High volatility in product markets	Reduced volatility exposure through diverse by-product valorisation
Inadequately developed product markets	Market creation through collaborative partnerships
Need for continual innovation	Improved innovation capabilities together with synergy partners.

Within the dynamic and rapidly evolving environment affecting the industry, industrial symbiosis approaches are also an important way of providing diversity, adaptability and cohesion to biofuel actors, thereby improving their resilience. In order to capture the value of industrial symbiosis approaches, on the other hand, biofuel players need to develop inter-organisational and cros-sectoral collaborations with actors that may like outside the traditional organisational field within which biofuel actors typically operate. To succeed in developing and maintaing such collaborations, biofuel actors need to develop a network of relationshiops that improve mutual understanding and trust among relevant actors, or improve relational capacities. This may help reduce the risk persception of actors and allow them to consider a wider range of opportunities as viable. Biofuel players also need to work with other actors and improve collective abilities to generate, share ant utilise relevant information–or enhance knowledge capacities. This will allow the actors to recognise a new range of feasible collaboration alternatives. Last, but not least, biofuel actors and others will need to improve their capacities to mobilise on identified opportunities, by identifying and engaging key parties that can contribute to the realisation of identified opportunities.

While the importance of industrial symbiosis for the emergence and development of bio-based industries, where biofuels are a part, is commonly recognised hypothetically, this study aimed at advancing understanding of the actual contribution provided in real life examples. These examples are among Sweden's leading with regards to how industrial symbiosis contributes to the successful development of biofuel industry. They can also serve as international examples of excellence. As mentioned in the analyses, these developments are strongly supported by various policies at EU, national and local levels–such as the carbon taxation in Sweden and the progressive climate impact reduction efforts at the level of municipalities. The main contribution of this study, on the other hand, is made by highlighting the importance of organisational factors that determine the relational, knowledge, and mobilisation capacities of relevant actors, thereby influencing both the identification and realisation of techno-economically feasible synergistic opportunities. Alignment of strategic objectives and organisational cultures, intensity and quality of communication, inter-organisational knowledge exchange and learning, formulation of effective and efficient governance mechanisms, trust, and level of support from different public governance levels are emphasised for their important role. Business benefits of industrial symbiosis and the role of organizational and institutional factors were then reviewed for two operational cases–a grain based ethanol production system and a co-digestion based biogas production system.

As Sweden's only large-scale grain-ethanol producing actor, Agroetanol, was acknowledged to be highly susceptible to commodity volatilities and over the years has faced serious challenges triggered by, among others, high grain prices, changes in the political support structures, competition from imported ethanol, and declining demand in the Swedish market. Nevertheless, the company was able to improve its cost efficiency and competitive position over the years through strategies of integration, diversity, adaptability and cohesion. In its pursuit of "scale economies" the company was able to drastically expand the volume of an earlier synergistic partnership, thereby securing competitively priced green energy. With "economies of scope" gaining increasing importance, the company developed new symbiotic partnerships enabling diversification and differentiation of its outputs as well as critical production inputs. It has adapted to the opportunities presented in the local operational context and in its conventional value chains, as well as to those arising in international niches. Thanks to these symbiotic relationships the company was able to increase its overall productivity, reduce energy and feedstock costs, reduce its exposure to market volatilities, and improve its environmental performance resulting in a premium in selected markets (e.g. in Germany, where financial incentives in proportion to actual CO2 performance is in place). Going beyond these by-product and utility synergies, the company has enhanced its cohesion and created new and strategic partnerships with diverse actors from different sectors allowing it to create and/or access innovative niche markets. Ability to identify and value resources and capabilities of other actors (both within and outside the corporate group), forming trusting relationships with reliable partners, and formulating and implementing business models and governance structures that incentivise relation-specific investments, knowledge exchange and learning have been key organisational and social factors that enabled the emergence and development of strategically important symbiotic relations.

In its evolution, the company has been gradually transforming from a biofuel plant into an increasingly complex bio-refinery, which is also coupled with a change in self-recognition: rather than being a sole biofuel producer, the company now sees itself a capable and willing actor which can actively support a shift towards a renewable and sustainable society with contributions within the transport, chemistry, materials, food and feed sectors. The company also recognises that in order to succeed in such ambitions, it will need to form new synergistic partnerships that will enable the creation new value chains and creation of additional value for existing and new customers in innovative ways. Such partnerships will be needed not only with other industrial actors, but also with academia, regulators and governance bodies.

The primary focus within biofuel development work predominantly stays on production and upstream operations and consequently the value of synergistic possibilities are mainly discussed within that frame. However, the development of the markets for biofuels, and bio-based products, are equally important (e.g. Ekman, 2012; Hellsmark et al., 2016) and the symbiotic partnership between the ethanol producer and the vehicle producer Scania serves as a valuable example of how industrial symbiosis enables the creation of niche markets for core products. While also serving as critical stepping stones for bio-based and biofuel developments, these kinds of partnerships also have implications for the further development of the industrial symbiosis field, which inadequately addresses the innovations directly linked to core businesses.

The biogas co-digestion plant has also been faced with similar challenges as the ethanol production. The plant's pursuit of scale economies, combined with competing demands on the conventional substrate streams, required access to new substrate flows. This has been addressed through gradually expanding utilisation of organic household waste, which brought implications such as increased transportation and pre-processing, reduced yield, increased digestate production, and shorter-term contracts with a larger range of substrate providers. The company offset some of these negative developments by creating new technical and administrative synergies with other utility operations. Most notably, energy costs were reduced and marketable gas production was increased by the use of district heating as process heating source, efficient access to substrate was enabled through better integration with municipal solid waste management system, and overall gas productivity was improved through utility synergies with municipal wastewater treatment operations. The plant was also able to secure more stable access to substrate from local industries and other municipalities through bundled utility service offers. Operationalising these synergies were greatly assisted by the different utility operations being under the same ownership, which assists strategic alignment among different units and reduces transcation costs among them. The strategic alignment between the biogas producer (Tekniska Verken) and the main customer for the produced biogas (Östgötatrafiken)–both of which are politically motivated entities– towards regional policy objective of increased utilisation of biogas as a transport fuel is another important enabler of successful synergistic relations. Similar integration and cooperation is likely to be technically possible in other contexts; however their realisation requires development of relational and mobilisation capital among actors, hindering developments. Reviewed biogas producer was also able to develop a strategic partnership, which allowed improved valorisation of biogas digestate in agriculture. This partnership was strengthened over the years thanks to strong complementary among respective resources and capabilities, high compatibility of organisational values, and intense knowledge exchange and joint learning.

These findings of this study regarding the wider business implications of industrial symbiosis for biofuel actors are strongly aligned with the conclusions of another study recently conducted by Peck and friends (2016), who stated that “the pursuit of cross industry and multi-faceted synergies will improve the strength of [a new biofuel development] initiative – and may be crucial to success.” (Peck et al., 2016).

It needs to be emphasised that the core actors covered in these study succeeded in strategically important symbiotic linkages by primarily relying on their own resources and networks, and without any dedicated third-party support. Nevertheless, as established by the industrial symbiosis literature, development of symbiotic linkages can be assisted by dedicated coordination efforts. Different actors, including municipalities, business associations, as well as initiatives like f3, can serve such function[18]. For example, creation of regional platforms can stimulate guided communication and interaction among diverse actors and facilitate information exchange, which will help build knowledge and relational capacity for new synergistic developments. More systemic data collection and analyses, on the other hand, can help identify more partnership opportunities. For cases where local governance bodies are involved in coordination, mobilisation capacities can also be enhanced through supportive planning, permitting and other approaches that can help overcome identified barriers. Given that symbiotic relationships help with competitiveness of all involved actors (and not only biofuel sector) and assist regional development, local governance actors taking on such roles would be sensible.

Although biofuel developments are important in their own right, they should not be treated as an isolated issue. Up until now, policy push rather than a market pull has played a key role for biofuels developments in contexts like the one in Sweden. Whichever the reason, this has lead to considerable developments, which has importance beyond biofuels alone. Both in the EU and in Sweden, a transition towards a bio-economy is increasingly supported. Bio-refineries are expected to be the engines of bio-economies, however it is not clear how their development can be achieved in the best way. Given the scale of needed investments, combined with political uncertainties, investments in grand new plants, using advanced technologies face significant challenges. A more feasible and robust strategy may be based upon existing actors and can be driven by diversification of products and increased integration and cooperation among both existing and newly established actors. As shown by the study cases, certain biofuel developments are increasingly acquiring the characteristics of bio-refineries, as a result of on-going evolution towards increased valorisation and diversification of products, inputs and partnerships. In this regard, focusing on biofuel developments only in their limited scopes will be misleading. Biofuel stakeholders are a part of a wider development enabling the replacement of fossil resources at a larger scale, for more purposes and in more parts of the economy and therefore all societal actors will be better served by acknowledging

[18] f3 is acknowledged for its role in strengthening the relationship between two of the actors which eventually developed an operational synergy.

their role as a stepping stone towards bio-refineries and take on the necessary challenges for their further developments. Although development of forestry based new value chains are regarded to hold the main potential for a transition towards a more bio-based economy in Sweden (Hellsmark et al., 2016; Peck et al., 2016), significant progress towards the development of bio-refineries, and thereby bio-based industries, has already been made, or under way, within alternative development paths relying on agricultural and municipal waste-derived feedstock. Successful development of innovative bio-based production units and bio-refineries, irrespective of their feedstock base, should be acknowledged for their important contribution for forming markets for more advanced materials and fuels and as kernels of a change that can result in more fundamental changes in the economic functioning. More systematically extracting and diffusing the lessons from these developments is important, on one hand, because further expanding bio-based industries making use of non-forestry feedstock needs to play a part in evolving towards a more bio-based economy. On the other hand, knowledge extracted from these operational examples can help overcome the barriers facing forestry-based developments. For example, Hellsmark et al. (2016) argue that there is a lack of knowledge and experience on system integration and institutional constraints. As manifested by the examples covered in this study, technical and managerial integration has already been developing, and constitute significant system strengths. Relevant knowledge and experience, therefore do exist, but are likely in need of transfer and translation to aid other development paths (forestry or marine based). Studied cases also demonstrate that biofuel developments can help strengthen other sectors and/or help address other societal challenges related to, for example, waste management, nutrition, or provision of quality services in urban settings (e.g. space heating). The biofuel systems that evolve towards increasing diversity of interactions with multiple societal actors offer meaningful contributions to a wider sustainable resource use base–going beyond a sole focus on transport. This recognition reinforces the importance of rolling out relevant public policies and private strategies that can support further development of mutually beneficial synergistic partnerships.

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APPENDIX: SELECTED TECHNICAL POTENTIALS FOR PRODUCTION SYNERGIES FOR BIOFUELS

Tables adapted from [1].

Table A 1. Biofuel → Biofuel Industry Synergies.

Potential Synergies	By-Product/Utility	Interaction
Corn Oil for biodiesel production [2]	By-Product	Ethanol-Biodiesel
Ethanol DDGS and syrup for biogas production [2]	By-Product	Ethanol-Biogas
Ethanol stillage as biogas source [3, 4]	By-Product	Ethanol-Biogas
Ethanol production heat used for biogas process [5, 6]	By-Product	Ethanol-Biogas
Oil cake as biogas source [7]	By-Product	Biodiesel-Biogas
Glycerol to biogas production [8, 9]	By-Product	Biodiesel-Biogas
Glycerol used to produce ethanol [10]	By-Product	Ethanol-Biodiesel
Anaerobic digestion of microalgae residues from biodiesel production [11]	By-Product	Biodiesel-Biogas
Ethanol production from biodiesel by-products [12]	By-Product	Biodiesel-Ethanol
Biogas production of ethanol by-products [13]	By-Product	Ethanol-Biogas
Integrated ethanol, cattle production and biogas to close material loops [14]	By-Product	Ethanol-Biogas
Industrial CO2 used for methanol production [15]	by-Product	Biofuel General-Biofuel General
Integrating biofuel production to produce ethanol, biogas and biodiesel [16]	By-Product	Biofuel General-Biofuel General
CO2 from ethanol production used for algae for biodiesel production [17]	By-Product	Ethanol-Biodiesel
Ethanol Stillage used for Biogas Production and CO2 used for algae [3]	By-Product	Ethanol-Biogas
Exhaust emissions from Biogas Producer sent to Ethanol Producer for combustion/Odor Control [18]	Utility	Biogas-Ethanol
Sulfur is a bad input for biogas production. Need a better way to control pH at Ethanol Producer. Biogas Producer prefers Nitrogen instead of Sulfur[18]	By-Product	Ethanol-Biogas
Refine the digestate to extract fatty acids and phosphor[18]	By-Product	Biogas-Biodiesel
Gas produced at Ethanol Producer - Sent to Biogas Producer for upgrading[18]	Utility	Ethanol-Biogas
Exhaust emissions from Ethanol Producer to dry digestate[18]	Utility	Ethanol-Biogas
Fusil/Other Alcohols from Ethanol Still used for biodiesel production[18]	By-Product	Ethanol-Biodiesel
Ethanol used for Biodiesel Production[18]	By-Product	Ethanol-Biodiesel
Oil from Wheat/Corn/Other starch crops for ethanol, pressed, oil expelled and used for biodiesel [18]	By-Product	Ethanol-Biodiesel
Pelletizer at Ethanol Producer employed with Digestate from Biogas Producer to make biomass pellets for fuel or feed[18]	Utility	Ethanol-Biogas
Biomass from ethanol production (other than stillage) used for biogas production[18]	By-Product	Ethanol-Biogas
Use stillage for biogas production only[18]	By-Product	Ethanol-Biogas

Glycerol produced from biodiesel production for biogas production[18]	By-Product	Biodiesel-Biogas
Glycerol + Fatty Acids (Biogas by-product) used for creation of monoglycerides for production of Biodiesel Feedstock[18]	By-Product	Biogas-Biodiesel
Seed cake and shells from biodiesel processing could contain starch and thus make ethanol[18]	By-Product	Biodiesel-Ethanol
Waste heat from ethanol and biogas facilities used in biodiesel production[18]	Utility	Ethanol-Biodiesel

Table A 2. Biofuel→External Industry Synergies from Literature Review

Potential synergies	By-Product/Utility	Interaction
Ethanol DDGS for human food applications [19, 20]	By-Product	Ethanol-Food/Feed
DDGS for animal feed [20, 21]	By-Product	Ethanol-Food/Feed
Integration with Extrusion technology for food/fodder production [21]	Utility	Ethanol-Food/Feed
DDGS used as filler for bioplastics [2, 21]	By-Product	Ethanol-Materials/Building
Ethanol By-Products for Fertilizer Production [2]	By-Product	Ethanol-Agriculture
Ethanol By-Products for Construction materials [2]	By-Product	Ethanol-Materials/Building
Biogas digestate used as solid fuel [22]	By-Product	Biogas-Energy/Fuel
Digestate used as particle board fibers [23, 23]	By-Product	Biogas-Materials/Building
Digestate used as fertilizer [24]	By-Product	Biogas-Agriculture
Biogas digestate used as feed [25]	By-Product	Biogas-Food/Feed
Biodiesel by-products used as carbon filters[26, 27]	By-Product	Biodiesel-Env. Services
Glycerol used as animal feed [28]	By-Product	Biodiesel-Food/Feed
Glycerol used to produce hydrogen [29, 30]	By-Product	Biodiesel-Energy/Fuel
Glycerol used as gasoline additive [31]	By-Product	Biodiesel-Energy/Fuel
Glycerine used as a fuel [32]	By-Product	Biodiesel-Energy/Fuel
Glycerol used for combustion [33]	By-Product	Biodiesel-Energy/Fuel
Biofuel by-products (DDGS; rapeseed cake and digestate) for combustion [34]	By-Product	Biofuel General-Energy/Fuel
Conversion of glycerol to glycolipids [35]	By-Product	Biodiesel-Chemical/Cosmetics
Chitin-glucan complex production from biodiesel by-products [36]	By-Product	Biodiesel-Chemical/Cosmetics
Biofuel production residues used as soil amendments [37]	By-Product	Biofuel General-Env. Services
Glycerol used as dust suppressant [38]	By-Product	Biodiesel-Env. Services
Glycerol used as carbon source to produce biosurfactant[39]	By-Product	Biodiesel-Chemical/Cosmetics
Glycerol and spent earth from biodiesel production used to produce clay bricks [40]	By-Product	Biodiesel-Materials/Building
Biogas digestate used as solid fuel [22]	By-Product	Biogas-Energy/Fuel
Sugarcane ethanol by-products used as cattle feed [41]	By-Product	Ethanol-Food/Feed
Distillers dried grain with solubles (DDGS) used in cornbread production [42]	By-Product	Ethanol-Food/Feed
Sweet corn tassels from ethanol production used as replacement to peat moss in greenhouses [43]	By-Product	Ethanol-Agriculture

Wheat protein, in aqueous ethanol, used for production of particle-bonding composites [44]	By-Product	Ethanol-Materials/Building
By-products from ethanol and biodiesel production used for biocomposites[45]	By-Product	Biofuel General-Materials/Building
Combustion of DDGS as a fuel source [2, 3]	By-Product	Biogas-Energy/Fuel
Carbon dioxide from biogas upgrading for greenhouses/plant source [46]	By-Product	Biogas-Greenhouse
Biogas digestate used for vermitechnology[47]	By-Product	Biogas-Agriculture
Digestate and CO_2 used as fertilizer/nutrients in greenhouses	By-Product	Biogas-Greenhouse
Dry digestate and use it as fodder	By-Product	Biogas-Food/Feed
Digestate used as bio-fertilizer	By-Product	Biogas-Agriculture
Separate nutrients in digestate for chemical processing	By-Product	Biogas-Chemical/Cosmetics
Gases other than methane and CO_2 captured and stored (e.g. H_2)	By-Product	Biofuel General-Chemical/Cosmetics
C02/Water from Ethanol production for Algae Production	Utility	Ethanol-Algae
Wet Stillage used for Animal Feed Direct (no drying)	Utility	Ethanol-Food/Feed
Dry stillage for biofertilizer	By-Product	Biogas-Agriculture
Waste water used for algae cultivation	Utility	Biofuel General-Algae
Glycerol used as binding agent for wood pellets	By-Product	Biodiesel-Energy/Fuel
Use stillage for pellet production (energy)	By-Product	Ethanol-Energy/Fuel
Glycerol for healthcare and cosmetics industry	By-Product	Biodiesel-Chemical/Cosmetics
Glycerol combusted at other industries for energy	By-Product	Biodiesel-Energy/Fuel
Glycerol from Swedish biodiesel used for "Swedish Eco-Soap"	By-Product	Biodiesel-Chemical/Cosmetics
Glycerol used as a carbon source in biological cleaning steps	By-Product	Biodiesel-Env. Services
$C0_2$ trapped from Ethanol, Biogas production for Greenhouses	By-Product	Biofuel General-Greenhouse
$C0_2$ capture at Ethanol and Biogas Plants	By-Product	Biofuel General-Chemical/Cosmetics
Waste water from biodiesel or ethanol production used for Salix production	By-Product	Biofuel General-Agriculture
Waste heat from ethanol, biodiesel and biogas production used in swimming pools/swim halls	Utility	Biofuel General-Municipal
Waste heat from ethanol, biodiesel and biogas used in nearby greenhouses	Utility	Biofuel General-Greenhouse

Table A 3. External → Biofuel Industry Synergies from Literature Review.

Potential synergies	By-Product/Utility	Interaction
Bioethanol from food residues (bread, kitchen wastes, etc.) [48-50]	By-Product	Food/Feed-Ethanol
Paper sludge for ethanol production [18]	By-Product	Forestry/Paper-Ethanol
Cheese whey lactose for ethanol production [51-53]	By-Product	Food/Feed-Ethanol
Biomass Wastes as biogas source [54]	By-Product	Forestry/Paper-Biogas
Food industry wastes as biogas source [55, 56]	By-Product	Food/Feed-Biogas
Fruit industry wastes as biogas source [57]	By-Product	Food/Feed-Biogas
Animal by-products as biogas source [58, 59]	By-Product	Food/Feed-Biogas
Dairy wastes as biogas source [60]	By-Product	Food/Feed-Biogas
Processing waste water for biogas production [61]	By-Product	Municipal-Biogas
Biodiesel from waste oils [62-64]	By-Product	Food/Feed-Biodiesel
Biodiesel from sewage sludge [65, 66]	By-Product	Municipal-Biodiesel
Biodiesel production from tall oil fatty acids [67]	By-Product	Forestry/Paper-Biodiesel

Meat industry residues for biodiesel production [68-70]	By-Product	Food/Feed-Biodiesel
Municipal Sewage Sludge for Biogas Production [71]	By-Product	Muncipal-Biogas
Ley crops used for biogas production [72]	By-Product	Agriculture-Biogas
Anaerobic digestion of household food waste [73, 74]	By-Product	Municipal-Biogas
Integration of ethanol production into a combined heat and power plant [75]	Utility	Energy/Fuel-Ethanol
Wastewater algae used to produce acetone, butanol and ethanol [76]	By-Product	Algae-Ethanol
Other fatty acids for biodiesel production, MeOH, Prop-OH, etc.	By-Product	Chemical/Cosmetics-Bio-diesel
Potato Chip/Snack Food waste vegetable oil (WVO) used for biodiesel production	By-Product	Food/Feed-Biodiesel
Potato Chip/Snack Food by-products (organic) used for bio-gas production	By-Product	Food/Feed-Biogas
Potato Chip/Snack Food by-products (Potato Skins) used for ethanol production	By-Product	Food/Feed-Ethanol
Animal fats from slaughtering at nearby farm used for bio-diesel	By-Product	Food/Feed-Biodiesel
Animal Wastes from farm used for biogas production	By-Product	Food/Feed-Biogas
Collaboration with municipal fat collector for biodiesel pro-duction	By-Product	Municipal-Biodiesel
Use fat separators from car washes, restaurants, etc. for bio-diesel production (if quality is low, for biogas production)	By-Product	Municipal-Biodiesel
Flour production must separate all oil in flour to increase shelf-life. Used for biodiesel.	By-Product	Food/Feed-Biodiesel
Algae from sea used for biogas production	By-Product	Algae-Biogas
Household wastes for biogas production (organic material --> Biogas)	By-Product	Municipal-Biogas
Household wastes for ethanol production (fruits, shells, etc. ---> ethanol production)	By-Product	Municipal-Ethanol
Other industries with WVO used for Biodiesel production	By-Product	Food/Feed-Biodiesel

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