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Industrial symbiosis in the energy sector

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1.1. Introduction

The concept of Industrial symbiosis was during the nineties by many researchers given key role in future industrial systems (Ehrenfield 2004). The closed energy and material loops was believed to entail a promising way in which future industrial systems could be designed so that the environmental impact from industrial operations in theory could be close to zero.

The purpose of this paper is twofold: First to explore how complex energy systems fuelled by biomass and waste materials could be optimized using the philosophy behind the industrial symbiosis concept. And second to unfold the recent development of the industrial symbiosis concept and elaborates on how it could be further developed.

Uncertain supply of fossil fuel and worries over the environmental and social effects of green house gas emissions have lead companies and public authorities to focus on how the use of biomass for energy generation purposes can be optimized. This paper explores how the concept of industrial symbiosis can support and optimize the utilization of biomass for energy purposes. The analysis is based on a system perspective where the entire energy chain is taken into consideration.

The paper is based on a research project conducted in the region of Zealand in Denmark where different types of biomass utilization was examined – all based on the concept of industrial symbiosis. The primary objective of the project was to promote sustainable utilisation of biomass waste for energy purposes in the Region of Zealand in Denmark. This involved assessing technical, economic and environmental aspects of the current and potential future utilisation of biomass waste.

The research project was theoretically based on the concept of industrial ecology and waste stream analysis. The idea behind the project was to analyse the production and utilisation of biomass waste in order to optimise bi-product utilisation and energy recovery.

The project was based on an extensive mapping exercise in which biomass wastes across sectors such as the agriculture, forestry and the industry was quantified for the region of Zealand. The identification of biomass waste streams for the region was then used in an analysis of the current use of the biomass waste followed by an evaluation of alternative ways of using the biomass waste. The suggested alternative utilisation included changes to existing plants as well as suggestions for alternative plants. The final output of the project comprised a number of shorter technical reports and pre-feasibility studies for the suggested alternative plants.

1.1.1. The ethical use of biomass for biofuel

The use of biomass to produce fuels (for electricity or transport) has caused a fierce political debate. High world market prices on food have particularly led to criticism from NGOs and various institutions. The European Union has responded to the criticism by including the so-called sustainability criteria's in the renewable energy directives that also contain the biofuel targets for the Union and its member states (EU 2009). The debate has led the Danish government to focus research and development funding on the so-called second-generation biofuels (The Danish Government 2007) that are produced from the fibrous biomass fractions, and thus not from human food. As a consequence of this political and ethical priority, the project is built around three ethical priorities, whereby it is not considered ethically justifiable to:

a) use areas where food can be produced for the production of energy crops

b) seize land and food resources from developing countries to produce biofuels

c) failing to exploit local available non-food resources in an era of limited fossil fuels and climate change

The priorities are politically motivated and require that agricultural land used for food production is not transferred to biofuel production. It also implies that it is to be considered unethical to use imported crops from developing countries that have been produced in a manner whereby the global food resources are reduced. In addition, it is not ethically justifiable not to bring the available non-food resources in use. The latter relates to the agriculture, the forestry, the animal production and for industrial waste and biomass-rich bi-products. Based on that, the focus in this project is on the production of biofuels from waste materials from industrial, forestry and agriculture or utilisation of energy crops grown in agricultural systems that does not reduce the production of food. The research project assessed the production of biofuels for transports purposes as well as the use of biofuels in electricity generation and district heating.

1.2. The concept of industrial symbiosis

Industrial symbiosis is a concept designed to describe and facilitate development of sophisticated industrial systems in which multiple companies' exchange by-products and in order to reduce raw-material and energy consumption (Chertow 2007). The extended bi-product and energy exchange was believed to entail a promising way of organising industrial activities, which in the future could lead the way towards more sustainable industrial production systems.

1.2.1. The origin of the concept

The concept of industrial symbiosis began to appear in academic literature in the late 1980's and the concept has since become a widely used by researchers and companies across the globe. The concept was derived from a couple of articles by Frosch and Gallopoulos (Frosch and Gallopoulos 1989) and Ayres (Ayres 1989), that emphasised extensive bi-product exchange between companies as a promising way out of growing environmental problems.

The concept described as industrial symbiosis is however far older than it appears to be in the academic literature (Desrochers 2002, Erkman 1997). Mutual use of residues should not be seen as a phenomenon solely associated with newer forms of industrial organization. A historical survey conducted by Desrochers

(2002) identified a large number of industrial symbiosis systems some of which dated as far back as the late nineteenth century, and thereby illustrated that the concept should not be regarded as a new phenomenon. The petrochemical industry has, for example, operated complex bi-product exchange systems for more than 50 years, although it was not, by the petrochemical companies themselves, labelled as industrial symbiosis. Nevertheless, the academic recognition of the potential for integrated production based on the strategic use all the waste streams appeared only within in the last two decades.

1.2.2. Bi-product exchange

What distinguishes industrial symbiosis from supply chain relations between two companies that exchange bi-products is that Industrial symbiosis involves more than simple re-use or linear exchange of residues between individual companies (Chertow 2007). The label of industrial symbiosis is deployed to describe more sophisticated industrial systems in which a number of companies are involved.

The motivation for the formation of industrial symbiosis is often found in a complex interaction of between various incentives (Altham & Berkel 2004). The most fundamental driver is that businesses by exploiting each other's residual or bi-products can reduce their costs (Heeres et al 2004). Bi-products which appear as a residue to one company are very often associated with a financial burden to dispose. The same bi-products can act as a valuable input to other companies. Besides the economic effects of the symbiosis, there is also an environmental benefit, which is related to the reduction of the total resource and energy consumption (Jacobsen 2006, Chertow 2007).

The optimised waste and bi-product use have proved to be an efficient way of reducing the total resource and energy consumption across the companies involved in the symbiosis (Jacobsen 2006). The reduced total resource and energy consumption may furthermore prove a way for companies to meet regulatory requirements which additionally will save the companies the costs of having to add end-of-pipe technologies to their plants. This has been a contributing factor to some firms who have implemented proactive environmental strategies to stay ahead of future environmental requirements. Such strategies often go hand-in-hand with corporate image and branding strategies.

1.2.3. The role of co-location

Co-location is often seen as an indispensable element of industrial symbiosis (Altham & Berkel 2004, Jacobsen 2006). Co-location is often seen as a condition which is needed in order to make the bi-product exchange function. From an environmental perspective, it is furthermore also often meaningful to reduce transport distances, as these will cause an environmental impact. However, maintaining co-location as a requirement for industrial symbiosis runs the risk of overlooking potentials associated with the creation of linkages between companies that are not co-located. Such linkages may prove to embrace huge potentials for increased resource-productivity and should therefore not be ruled out. Additionally, the potential for industrial symbiosis is likely to be significantly larger if co-location is abandoned as an absolute necessity, and instead only regarded as a factor that may be important in some cases - for example when the exchanged bi-product are inappropriate to transport over longer distances. It may in some cases prove to be a good idea to transport the bi-products over longer distances if the environmental and economic burden associated with long-distance transport proves less significant compared to the environmental improvements achieved from the bi-product exchange. Such types of industrial symbiosis may, from an academic point of view, be more difficult to identify, but need not be less interesting or relevant for that reason. The advantage in abandoning the necessity of co-location is supported by a study of German industries conducted by Sterr and Ott (2004) who found that an extension of the geographical scope of traditional Eco-industrial parks would increase potentials for bi-product exchange and provide a more promising frame for a sustainable closed-loop economy.

Co-location has therefore not been regarded as a requirement for industrial symbiosis in this project. The individual projects have been assessed on the basis of the potential synergies and environmental savings instead.

An article by Chertow (1999) identified five generic types of industrial symbiosis systems: 1) through market-based waste exchange where companies achieve multiple benefits but relies on a low degree of coordination, 2) within a single firm or organization where waste is exchanged within the boundaries of a single company located in one site or across multiple sites, 3) among co-located companies (eco-industrial parks), 4) among local companies that are not directly co-located but located in close proximity and 5) among companies in a regional setting, typically involving a larger number of companies but without overall coordination of the waste exchange. These different types of industrial symbiosis systems illustrate the complexity under which industrial symbiosis systems is organised in reality and gives recognition to fact that the conditions for waste utilisation and bi-product exchange differ widely across industries, sectors, geographic conditions and even from company to company.

The conceptualisation of industrial symbiosis, in this research project, as system which is independent of co-location, is to a large extent determined by the focus on biomass waste and the specific, contextual conditions that revolves around the utilisation of biomass for energy purposes. Energy generation from biomass waste usually requires large quantities of biomass. Feasible systems very often necessitate collection of biomass waste from a large geographical area. Take for example straw, which appears as a bi-product in the agriculture from the production of crops like weed. Straw is in the Danish energy system incinerated in combined heat and power plants. Such systems require large geographical areas and co-location of farms and power plants are undesirable as the combined heat and power plants are located urban areas so that the heat (which is a bi-product from the electricity generation) can be utilised in the district heating systems. Realff & Abbas (2004) additionally argues that the maximum transportation distance as a rule of thumb is 80 kilometres, when straw is utilised in bioethanol production.

1.3. Biomass and industrial symbiosis

The concept of industrial symbiosis is particularly relevant for the utilisation of biomass waste for energy purposes as the concept is designed to facilitate the optimisation of bi-product utilisation across companies. What makes industrial symbiosis relevant to utilisation of biomass waste is *first of all* related to the fact that biomass is a scarce resource. The total quantity of biomass that can be generated depends of course on a large number of variables (soil quality, choice of crop, precipitation etc.) but is ultimately restricted by the scarcity of arable land. Consumption of biomass in the energy sector competes over the use of biomass with other sectors such as the food producing sector.

It is vital, from a political and ethical point of view, that the consumption of biomass for energy purposes is design so it does not compromises global need for food. Utilising biomass waste and bi-products from agriculture forestry and the manufacturing industries is a way in which the energy demand can be met with a low net increase in CO_2 emissions without compromising the need for food. The idea behind industrial symbiosis interesting in that respect as it deals with the development of tools and guidelines on how to increase and optimise waste and bi-product utilisation. *Secondly*, energy production on the basis of biomass is associated with a generation of a number of different waste streams and bi-products. The character and quantity of the bi-products depends on the type of biomass which is used as and input (wood, straw, algae, etc.) and on the deployed conversion technology (e.g. incineration, anaerobic digestion, fermentation, extraction etc.). More simple systems such as incineration of straw in combined heat and power plants generate electricity and steam. Maximising the bi-product utilisation is in such systems is sensitive to the adaption to the regional electricity demand and local district heating system. More complex systems in which biofuel fermentation of for example straw is linked to CHP plants generate a larger diversity of bi-products and require more complex systems of bi-product exchange (DONG Energy 2006).

1.3.1. Linking companies across sectors involved in biomass production and utilisation

The scarcity of biomass resources is amplified by the fact that biomasses are utilised by companies across different sectors, all of which are likely to increase the consumption in the future. A number of factors are therefore expected to contribute to high future competition over biomass and biomass waste: production of bio-plastics, increased utilisation of biomass at CPH plants, biofuel production, and increased food production due to global population growth and changed consumption patterns in favour of meat consumption. Optimal use of the biomass is therefore a prerequisite for sustainable development. Optimal use of biomass necessitates a high degree of bi-product and waste exchange not only between companies within one sector but across companies in multiple sectors, in order to assure that the scarce biomass resources are completely exploited and not lost as waste along the value chains of various industries. These sectors include:

1. The agriculture: The agriculture is the most important supplier of biomass. The biomass production is dependent on a large number of variables. Advanced methods of cultivation combined with crop choice aimed at increasing the biomass output without compromising the supply of food and other vital products can increase the total biomass output.

2. The forestry: the forestry is in some countries a key supplier of biomass. The Danish production of biomass from forestry is far lower that that of the agriculture, but the forestry is nevertheless a vital biomass supplier. Quantities could be increased if alternative cutting and felling methods were developed and deployed.

3. The manufacturing industry: Biomass is utilised across many different manufacturing industries. Biomass is utilised as a raw material input in the manufacturing of furniture, wooden floors construction materials etc. Such industries very often generate substantial amounts of biomass waste that could be utilised for energy purposes.

4. The food industry: Production of various food products lead to generation of bi-products that can be utilised for energy purposes. The value chain of the food production is linked to the biomass

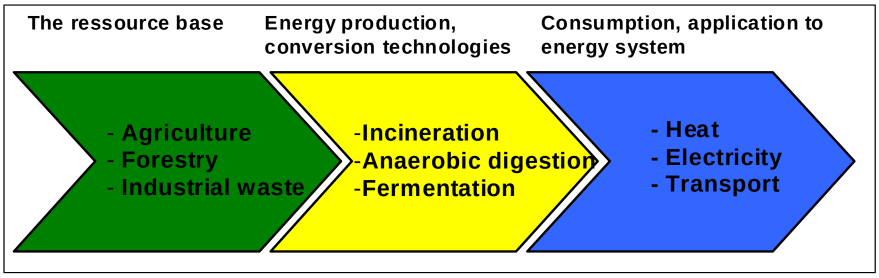
energy chain upstream as food products is based on biomass and downstream in the value chain as food production also generates waste and bi-products that contain biomass which can be utilised for energy production. The character of the waste and bi-products differs across the various types of food products. Slaughterhouses for example generate animal fat as a waste product that can be utilised in biogas or biodiesel production. Production of pectin also generates large quantities of biomass waste that can be utilised in biogas production.

5. The energy production: energy production, or the conversion of biomass to energy (electricity, heat or biofuel), is directly linked to the sectors mentioned above as it relies on biomass as an input. However during the conversion of biomass to energy also generates bi-products that are transferred back to the other sectors.

A key issue when linking these sectors is to ensure that all loops are closed so that all bi-products are utilised and no waste is generated during the production processes.

1.3.2. The biomass energy chain

Linking companies across industries is a complex task that requires collaboration between multiple stakeholders. The figure below illustrates the simple chain of links between the generation of biomass resources from the agriculture, the forestry and industrial waste products to the energy production and to the final consumption. It is important to understand that the efficiency of the system is closely related to the utilisation of waste streams from all links in the energy production chain. Each of the three elements in the chain would in reality therefore be interlinked by a complex web of feed-back loops in which waste products are transferred backwards in the chain to serve as inputs in the production of yet other products.



The complexity is under real life conditions far bigger than the illustration indicate. Biogas, to give an example, is in the region of Zealand, generated in anaerobic digestion from a combination of pig manure (agricultural waste) and slaughterhouse waste (industrial waste). The residue from the anaerobic digestion is transferred back to the agriculture and used as a high value fertilizer, which substitutes the use of imported energy intensive fertilizers. The biogas sold to a combined heat and power plant where it is incinerated to produce heat and electricity. The electricity is supplied to the grid and the co-generated heat is utilised in the district heating system. The symbiosis not only creates a number of high value products but also solves waste problems for the slaughterhouses and the pig production. Denmark, although only accounting for 5.5 million human inhabitants produce more that 25 million pigs per year. This extensive pig production system creates large waste problems as the spreading of manure on the fields leads to eutrophication in streams, bays and inner seas. The anaerobic digestion thereby on the one hand function as a waste treatment facility for the agriculture and the slaughterhouses but on the other hand creates high value products (electricity, heat and fertilizer) in it self.

1.3.3. Biomass production

This project analysed biomass production in the Region of Zealand, Denmark, in three sectors: the agriculture, the forestry and the aquatic environment.

The project also included an examination of the potentials for integration of energy crop with the conventional food and fodder production in the agriculture. This task led to the formulation of concepts for the multifunctional agriculture in which aspects such as biodiversity, ground water conservation, maximised yield and reduction of energy consumption was incorporated. The latter related to a reduction in the use of imported energy-intensive fertilizers by substitution with the residue from biogas production.

The idea behind the multifunctional agriculture is to develop agricultural systems which can enable the farmers to integrate energy crops in system without compromising the production of food, in line with the ethical code presented in the beginning of the paper.

1.3.4. The energy production

A key task of the research project was to establish links between the resource base and energy production part of the energy chain in order to optimise the utilisation of bi-products and improve overall energy balances.

The Danish electricity and heating system is comprised by a combination of centralized and decentralized plants. In 2000, 54% of a total of 2.5 million Danish homes were heated by heat produced in CHP plants. 17% were heated by small decentralized CHP plants, which are primarily located in smaller towns, and 37% were heated by large central CHP plants located in major cities (Danish Energy Authority 2005). The heat is sold to district heating companies often via transmission companies. District heating companies are typically either municipally owned or owned by consumers in a cooperative. Part of the municipally owned district heating companies are transformed into autonomous corporations as partnerships or limited liability companies (SA), which may be wholly or partially owned municipalities (Danish Energy Authority 2004).

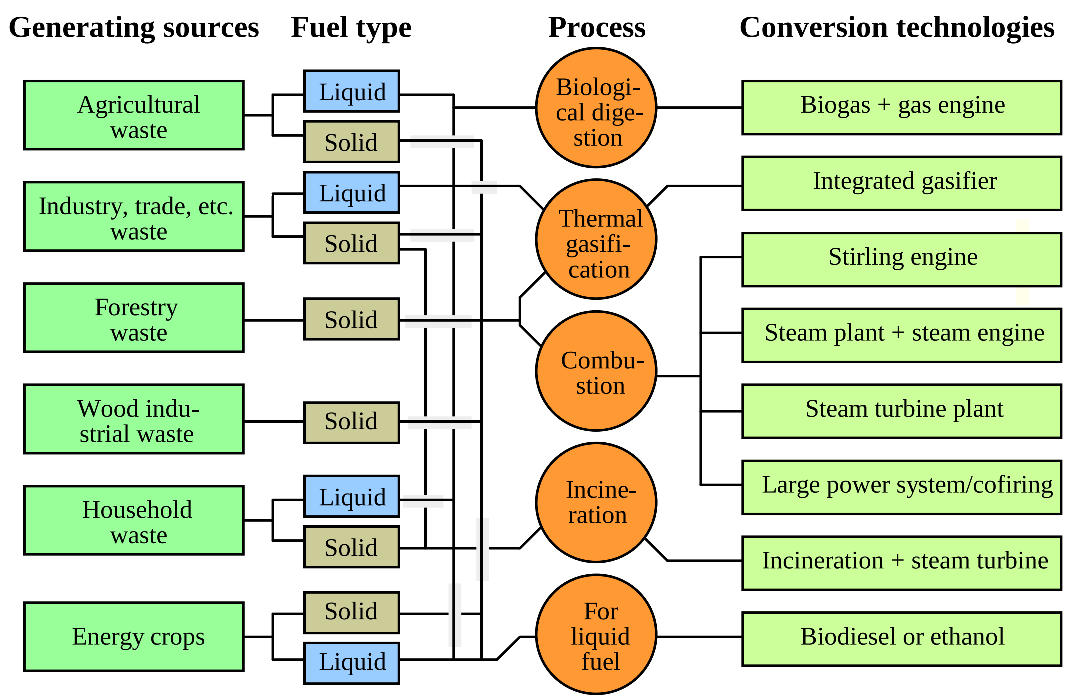
The incineration of coal, waste or natural gas results in heat that is converted to steam which is deployed in order drive turbines that produce electricity. Combined heat and power plants utilises the heat which would otherwise be ventilated in the air or cooled by sea water to heat houses via the district heating systems (Korhonen 2001). The co-production of electricity and heat has resulted in energy savings of around 30% (Danish Energy Authority 2004).

The centralised CHP plants were historically designed to generate electricity only while the decentralised plants were designed for heat production only. This system was changed and both the central and decentralized plants re-designed to produce combined heat and power. However approximately one third of the decentralized plants (130 out of 415 plants) are still only producing heat. Denmark has in total 16 central and 415 decentralized plants (Danish Energy Authority 2005). In addition there were in 2004 480 small CHP- and district heating plants, which were dedicated to specific industries, nurseries, schools or offices.

The generation of electricity and heat in the region of Zealand is managed by a combination of four central CPH fuelled by either coal, oil or biomass; a number of decentralized CHP plants, mainly fuelled by natural gas, serving the smaller cities; and a number of decentralized heating plants which are primarily based on biomass or natural gas. The region additionally hosts three larger biogas plants that produce a methane rich gas from a combination of animal manure and industrial waste. The gas is burned in an engine or a turbine for production of heat and electricity. The region of Zealand is characterised by large regional differences. The two islands Lolland and Falster differs from the rest of the region by the fact that the heat is produced in decentralised plants based exclusively on biomass.

1.3.5. Conversion technologies

There exist a large number of conversion technologies that can be deployed to generate electricity, heat or biofuel from biomass. Some of them have been used for centuries whereas others are still in their early development phases. Most of the conversion technologies produce several bi-products along the processes. The optimisation of the use of such bi-products between the various part of the energy chain is the greatest challenge to the energy system: maximizing waste and bi-product utilisation form agriculture, forestry, manufacturing industries and linking it to the optimal conversion technology and finally adapting the electricity and heat production to the local market for district heating and the national electricity consumption.



1.4. Symbiosis concepts for the energy sector

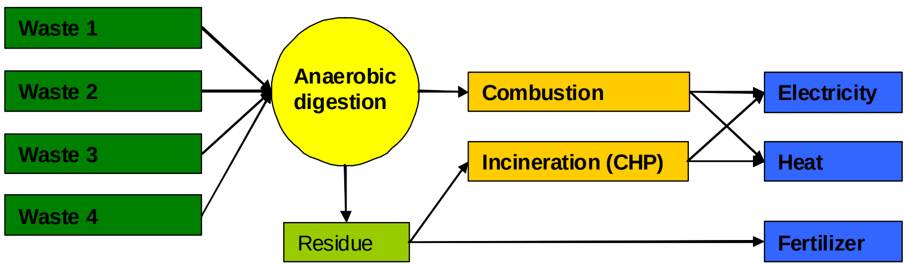
One of the objectives of this research project was, as stated in the introduction, to develop concepts for industrial symbiosis in the energy sector, based on biomass waste generated by the agriculture, the forestry and the manufacturing industry in the region of Zealand in Denmark. These concepts are subsequently intended to be applied as templates for a number of specific projects which will be established in various geographical sites in the region. The concepts should therefore be understood as ideal type concepts which need to be applied to the specific contexts which the specific projects are to be established.

The symbiosis concepts revolve around three selected conversion technologies: biogas, CHP generation on the basis of incineration and IBUS 2. generation bioethanol fermentation technology. The conversion technologies were selected on the basis of an analysis of 1) the available biomass resources in the region, 2) competences in the region (some of the conversion technologies were already in use in the region), 3) the structure of the local energy demand (primarily in terms of integration into the local district heating systems in the region) and finally 4) as the most important issue the potentials for optimisation.

The result of the analysis was the identification of four generic concepts for industrial symbiosis in the energy sector:

<u>Concept 1</u>: Small scale biogas based on a broad range of resource:

The first concept is a concept for a small biogas facility (approximately 2MW) which is to be linked upstream in the energy chain to a broad range of locally generated biomass resources. It is linked downstream to the local district heating system (heat), local agriculture (fertilizer) and national electricity grid (electricity).

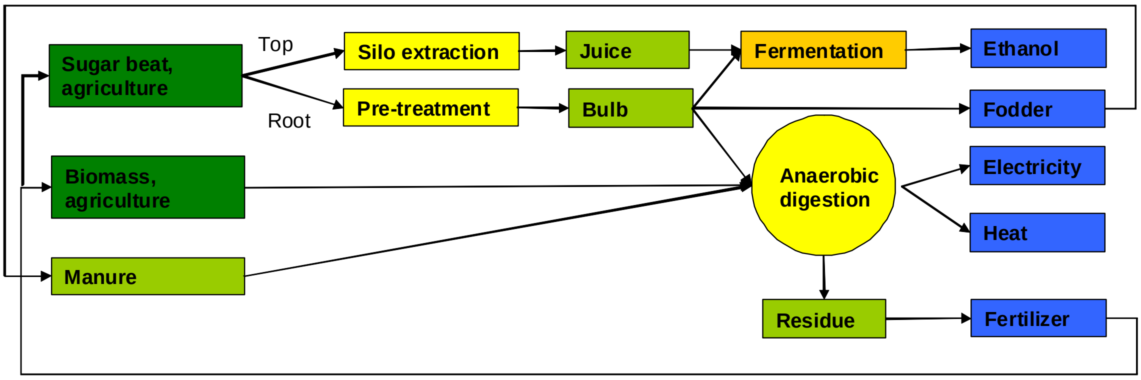


The central conversion technology is the anaerobic biogas production. Biogas is the term for gas produced from biomass and waste, which is rich in methane (60-70% CH4 and 30%CO_2). It can be produced by the fermentation of animal dung, human sewage, crop residues or organic industrial waste. These inputs are often mixed in order to maximize the gas production. The biogas is produced in an air-tight container and the produced gas is deployed to generate electricity and heat when combusted in an engine or turbine. The residues of biogas production are used as a fertilizer in the agriculture to substitute imported fertilizers.

The system presented as concept 1 use a broad range of inputs for the biogas plants. Some of these may be contaminated with heavy metals if the waste is sourced from wastewater treatment facilities or industries. The residue can therefore not always be used directly as fertilizer for the agriculture. The system therefore includes the option of residue incineration.

<u>Concept 2:</u> medium sized biogas facility linked to the multifunctional agriculture

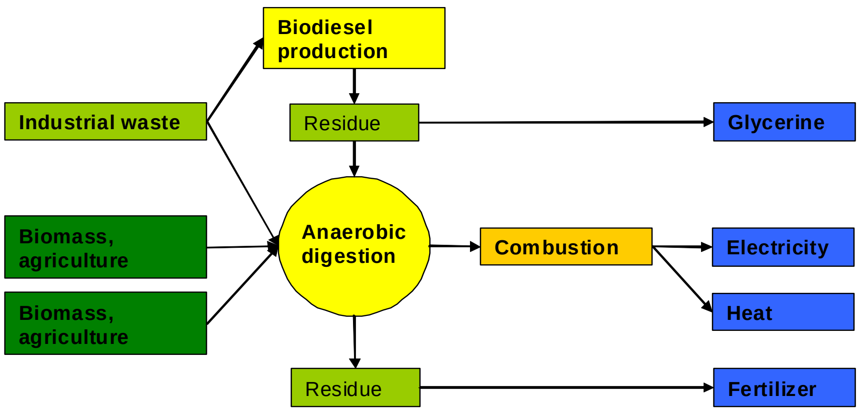
The second concept is a concept for a medium sized biogas facility linked to the multifunctional agriculture. The system illustrated below is an agricultural system based on sugar beet. The reason for selecting sugar beet is two fold. The sugar beet first of all gives a high biomass yield per acre compared to crops like wheat. The second reason for selecting sugar beet is that the farmers in the southern part of the region have a long tradition for sugar beet production and therefore are more likely to engage in the system if their knowledge and know-how is acknowledged and utilised. The sugar beet is planned to be grown in a crop rotation system with 4-6 other crops. One of these is clover which is fed into the biogas plant. The clover first of all ensures a high amount of biogas production. The biogas facility secondly generates a residue which can substitute the need for imported, energy-intensive fertilizers. This feature thereby adds to the total CO_2 abatement form the system and provides an ethanol fuel for the transport sector which has a higher CO_2 abatement and consequently makes it easier for the fuel providers to comply with the sustainability cirteria's in the European Union Renewable Energy directive (EU 2009).



The concept illustrated above includes a decentralised silo storage system for the sugar beet top. The root is pre-treated at two stations. The root is first cut into small pieces and afterwards pressed. The juice which is rich in sugar can then be fermentated into ethanol in a low cost 1. generation system that renders the use of expensive enzymatic treatment obsolete. The residue from the bulb can subsequently be used as animal feed or as input for the biogas plant.

<u>Concept 3</u>: medium sized biogas facility linked to established industries and energy crops

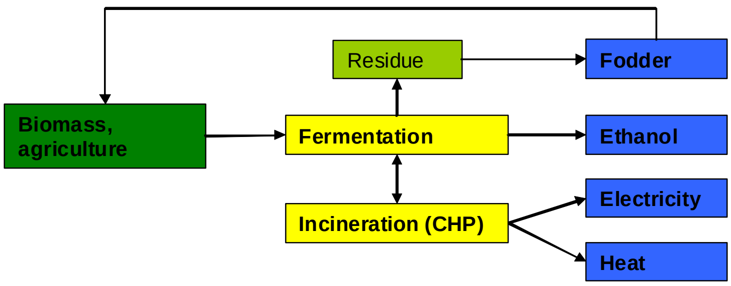
The third concept is a concept for a medium sized biogas facility linked upstream to a combination of larger established industries such as slaughter houses and energy crops grown in the multifunctional agriculture systems. The system will be linked downstream to the local district heating system (heat), local agriculture (fertilizer) national electricity system (electricity).



The system illustrated above combines two biofuel production lines. One that converts slaughterhouse waste (fat) into biodiesel and a second one which use the slaughterhouse waste directly in the biogas reactor. The two systems can also be combined in a system in which the residue (glycerine) from the biodiesel is utilised in the biogas plant. The use of the residue from the biodiesel production will be determined by the market price for glycerine as glycerine is also used in competing products.

<u>Concept 4:</u> IBUS 2. generation bioethanol fermentation linked to CHP plants

The fourth concept is a concept for 2. generation ethanol fermentation of straw. The system is based on the so called IBUS (Integrated Biomass Utilisation System) system. The IBUS system is a concept for bioethanol production based on lignocellulosic feedstocks.



The IBUS system is yet not fully developed. A demonstration plant is presently (2009) under construction in Kalundborg. This plant will supply solid biofuels (lignin) to the Asnæs power plant, which is located in close proximity, and in return receive water and heat. The IBUS bio-ethanol facility will thereby be integrated into the established industrial symbiosis in Kalundborg (Dong Energy 2006).

The integration between IBUS bioethanol production and CHP production is essential as high carbon abatement is reliant on the utilization of the lignin that appears as a bi-product from the production of bioethanol. The heat which is generated from the incineration of the lignin can subsequently be used in bioethanol production. The other bi-product is a high quality animal fodder.

The integration between CHP and IBUS ethanol production is from an economic perspective also interesting as the integration would render the construction of a separate boiler for the burning of lignin unnecessary. This would in turn reduce construction costs. An American feasibility study, prepared by National Renewable Energy Laboratory (2002), of a bioethanol plant, found that construction of a separate boiler for combustion of lignin would add 30% to construction costs compared to a plant established near-by an existing coal-fired power plant.

The integration with the existing heat and power system requires that the biofuel production is dimensioned according to the need for heat in the local district heating system. This fact makes some sites more suitable for bioethanol production than others. The dimensioning of the biofuel production is especially relevant if the biofuel production is established in relation to small scale district heating systems.

1.5. Conclusion

This paper concludes with the presentation of four industrial symbiosis concepts which was developed as templates for a number of specific projects which will are intended to be established in at sites in the region closely integrated with the biomass waste resource base and the district heating systems. The four concepts comprise a novel, cross-sectoral approach to energy generation based on biomass and waste materials in which full energy chain is considered with the aim of optimising bi-product utilisation. The four concepts for industrial symbiosis in the energy sector are furthermore intended to illustrate how a decentralized energy system can be developed and implemented in order to facilitate increased use of renewable energy in the energy sector.

The paper finally concludes that the energy efficiency rates for energy generation based on biomass are closely reliant on the utilization of waste streams: in a simple system the utilization of co-generated heat and in more complex systems the utilization of all waste streams. The overall system efficiency of a complex system will only reach the highest efficiency if waste streams in all links of the biomass the value chains is utilized.

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