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Innovation and Creativity

Development and assessment of symiosis in an industrial park

Øystein Hjelm

Master of Science in Energy and Environment
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Supervisor: Anders Hammer Strømman, EPT
Co-supervisor: Audun Amundsen, Kjelforeningen Norsk Energi

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Problem Description

Background

The seriousness in the global environmental situation has led to an increasing acknowledgement that a change of paradigm is needed to secure a sustainable development. This comprises a more efficient and environmentally friendly utilization of the resources currently used. In this context, the organization of industrial activities in such a manor that they could utilize each others by-products in a symbiotic network, has been seen has an important contribution to reduce the environmental impacts with in the industrial sectors. China has long been known for its many eco industrial parks. A rising interest for this alternative organization of industrial activities is also seen en Europe. In Great Britain a comprehensive network of regional centres to contribute to the development of industrial symbiosis has been set up. The increased interest also creates challenges in regards to developing tools to be used in analysis and design of industrial symbiotic systems. If a symbiotic project shall contribute to sustainable development it has to be appropriate in regards to both the environment and economy. It is therefore desirable to strengthen the experience of combing the use of tools for developing industrial symbiotic systems with cost and environmental impact evaluation methods.

Scope

With a basis in the planned and existing elements at the are of Mosseportn, the symbiotic network should be further developed to handle future changes in resource availability as a consequence of the prohibition of land filling of biodegradable waste. Potential new processes should be identified and introduced with the intention to evolve the symbiotic possibilities and thus increasing the value added and reducing the environmental impacts. The solutions should be evaluated in regards to environmental and economy.

The thesis is approached based on the following points:

1. A superior literature study on environmental and economic evaluations of a industrial symbiotic system shall be conducted.
2. The symbiotic network at the area of Mosseporten shall be further developed and a process simulation model shall be established.
3. Analysis of energy, exergy and resource flows shall be conducted.
4. An evaluation of the proposed design with regards to the environment and economy shall be conducted.

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POSTADRESSE
NTNU
INSTITUTT FOR ENERGI OG
PROSESSTEKNIKK
Kolbjørn Hejes vei 1A
N-7491 Trondheim - NTNU

TELEFONER
Sentralbord NTNU: 73 59 40 00
Instituttkontor: 73 59 27 00
Vannkraftlaboratoriet: 73 59 38 57

TELEFAX
Instituttkontor: 73 59 83 90
Vannkraftlaboratoriet: 73 59 38 54

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Ekstrakt

The paper treats the development of an eco industrial park in Moss. The EIP is based on landfill gas produced at Solgaard Landfill. The proposed system is evaluated using HYSYS, and the data is analyzed by considering flows of energy, exergy and resources. The system produces 35 per cent less emissions of carbon dioxide compared to stand alone units. Other then the heat required for the syngas reformer, the system produces enough heat, to cover the demand within the system. The system fulfils guidelines adapted from Kalundborg on how a park is considered. Both the energy and material flow analysis provided good results, while the exergy flows need better models when dealing with losses.

	Stikkord på norsk	Indexing Terms English
Gruppe 1	Øko industriell park	Eco Industrial Park
Gruppe 2	Industriell Økologi	Industrial Ecology
Egenvalgte stikkord		

“Adaptation means not clinging to fixed methods, but changing appropriately according to events, acting as is suitable.”

Zhang Yu

Preface

This project has been both challenging and frustrating. I have experienced the downside of not being in an environment where help and advice is only a few meters away. This has led to many frustrating moments, especially in the completion phase, when important decisions have had to be made. On the other hand it has been a valuable experience since it has thought me to make my own decisions in pressed situations. All of these decisions may not have been correct, but have been taken in a given situation. The main challenge connected to the project has been focus and motivation. Since the definition of the thesis was very wide I started looking for several solutions on how to solve the project. Finding solutions and being creative was very motivating and I used too much time on dead ends and wrong solutions. This led to a lack of progress, which led to an intensive last month of writing. A lot of work done, but thrown out is not shown in this paper. If this had been a Hollywood DVD it would have been packed with extra features not used in the movie. But, as a movie director, the choices made have thought me to prioritize and keep focus. And for this experience I am glad. I would also thank my supervisors Anders Strømman and Audun Amundsen for giving me the opportunity to work with a very interesting subject.

Øystein Hjelm, Oslo 16.06.2007

Comments on change of thesis description

In collaboration with my main teaching supervisor Anders Strømman, part of the project goal has been removed. As the project developed it proved that simulation work and technical analysis became too comprehensive to include an economical analysis. It has therefore been removed from the goal of the thesis.

Summary

As weather records are broken, and the topic of global warming and climate change, focus has been set on how this current development could be slowed or stopped. A change in paradigm must be conducted in order to address sustainable development. This paper has focused on how the field of industrial ecology and the tool of eco-industrial parks could be used to improve environmental performance of industrial systems.

To evaluate the methods an industrial area at Moss has been further developed and new processes have been introduced. The system consists of an oxy-fuel CHP with carbon dioxide capture using the landfill gas as fuel, a urea plant, an ammonia plant to deliver ammonia to the urea plant and a cryogenic air separator plant providing nitrogen to the ammonia plant and pure oxygen to the CHP. Some carbon dioxide not used in the urea plant is used to increase the growth in a greenhouse.

To evaluate the system, two simulation tools have been used. HYSYS has been used to simulate the processes involved and to arrange data for flow analysis. The heat exchanges had been assessed using Pro Pi 1, a tool specifically designed to create composite curves. Several simplifications have been made to easy the simulation.

The CHP has an electric efficiency of 27 per cent and a total efficiency of 73,8 per cent. The electric exergy efficiency of the CHP is 28 per cent with a total system exergy efficiency of 67,7 per cent. The proposed system emits 35 per cent less carbon dioxide compared with stand alone processes. The system produce more heat then is needed to cover almost every process, and also the total demand in both the low- and high temperature district heating. The only process in need of external heating is the syngas reformer, which operates at such a high level that a stream of 46 kg/h of methane must be added. The output form the park is 8120 tonnes of urea annually, based on 8000 operating hours.

The composite curves used to describe the heat exchange in the system proved to be a valuable tool when evaluating the need for utilities in the system. Both the material and energy flow analysis provided a good way to present energy and resource flows in the system. However, the exergy flow analysis proved to lack well developed tools to include irreversibility connected to the flows.

Based on the guidelines presented from the Kalundborg EIP, the designed system could be called an eco-industrial park. However, economic analysis must be conducted to explore if there are economic incentives for the companies to develop such a park.

Based on the experiences in this paper, further research should be made to develop better tools to calculate exergy losses based on HYSYS simulations. Also, an assessment of the economics connected to the system should be conducted.

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1 Introduction

As this introduction is being written Oslo has already experienced its first tropical day. This is the earliest record of such a day in 110 years, and the temperature of 31,1°C is the highest ever recorded on this day ever in Oslo. As the citizens of Norway enjoy the sunny day outside, such record braking days also send our thoughts to a literally hot topic; global warming. UN's panel on climate change has concluded with high confidence that several changes on biological systems have happened and will happen as a consequence of climate changes, and temperature increase in particular. The northern hemisphere, where Norway lies, will get higher temperatures and more precipitation. Mapping how the emissions of climate gasses influence our global climate, and how these emissions could be reduced, is of great importance. In Norway, the Norwegian Commission on Low Emissions has concluded that several measures could be taken within feasible economic boundaries to reduce Norway's emissions by two thirds. The measures are of both technical and social character. This complex approach is well covered in the field of industrial ecology. One of the field's tools developed is eco-industrial parks, where companies cooperate to produce a win-win-win situation; economic, environmental and social. This paper covers a suggested development of an industrial park in Moss. Several of the suggestions from the Norwegian Commission on Low Emissions are used in the development. The paper is divided into four main parts. The first part covers the concept of the greenhouse effect and the consequences they have on the global climate. Several measures to reduce the emissions both globally and specially in Norway are presented. The second part covers the concepts and tools used in the paper. The part presents the field of industrial ecology. An in-depth presentation of the concept of eco-industrial parks is then presented. A literary study of some cases has been conducted to show the benefits of the parks. This part is ended with a presentation of the engineering tools used to analyze the performance of the system. The third part contains a presentation of the case to be developed. Processes and fields in connection to the case are presented, followed by an explanation on how the system has developed and a presentation on each of the different processes being introduced into the area. In the final part the results of the simulations are presented and discussed.

2 Global Warming and Climate Change

Global warming and climate change has become household expressions in the last few years. From being a subject for NGO's, researchers and particularly interested citizens it is now atop of the political agenda and a consensus that this is a problem. But what is the problem? What are the consequences? And how could we avoid or reduce these? This chapter describes the concept of global warming and consequences and measurements both globally and nationally.

2.1 The Greenhouse Effect

The Greenhouse Gasses is a collective term for the gasses methane, carbon dioxide, nitrous oxide, chlorofluorocarbons (CFCs) and ozone. Apart from CFCs, the other gases exist naturally in the atmosphere and constitute the natural greenhouse effect. Without the presence of these gases the mean temperature on earth would be -6ºC instead of 15ºC [Smith R. T., Smith L. M., 2003]. They act like a blanket in the atmosphere, warming the earth. Figure 2-1 shows the naturally occurring greenhouse effect and energy balance. The energy balance and greenhouse effect could be explained by two physical effects; absorption and emissivity. They are strongly connected, and objects that are good absorbers have high emissivity. The opposite of absorption is reflection, and a good example of this is insulation which often has a glossy side to improve its abilities.

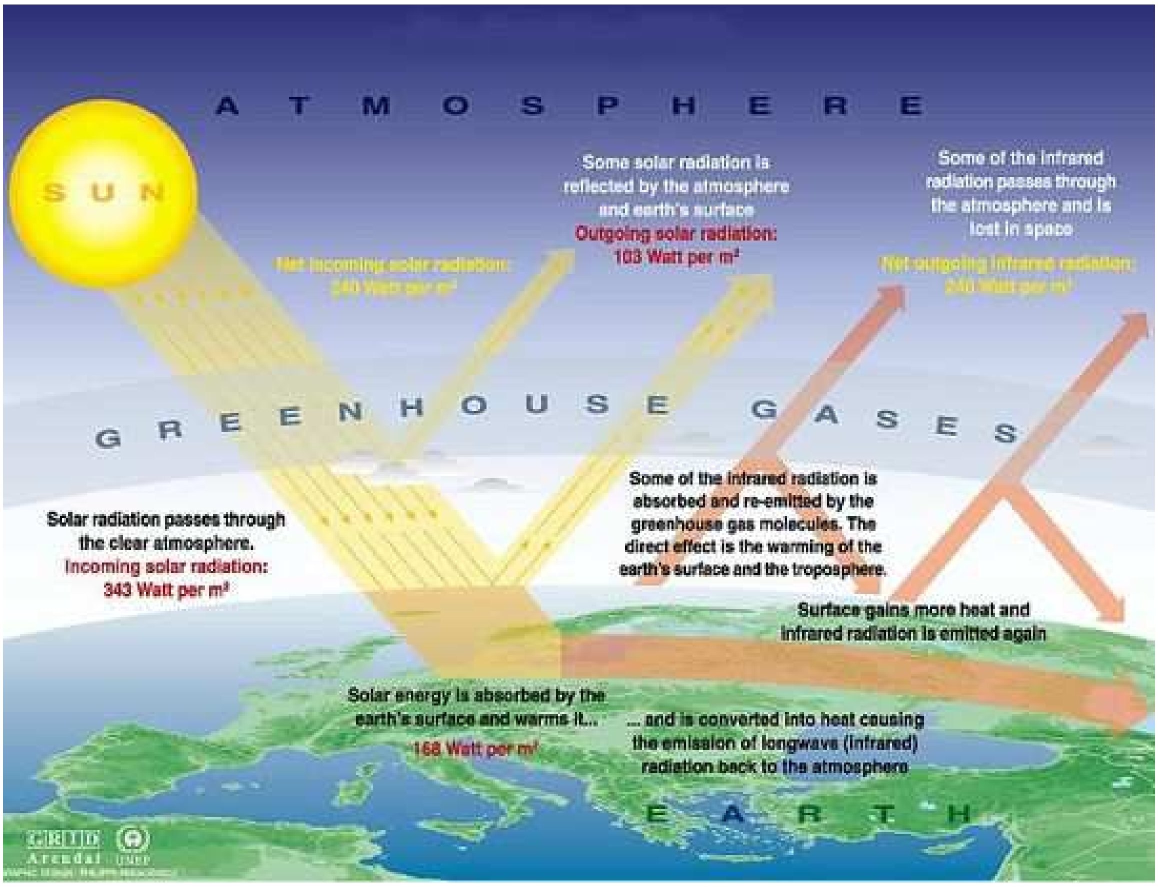


Figure 2-1: Natural greenhouse effect [NCRLC, 2005]

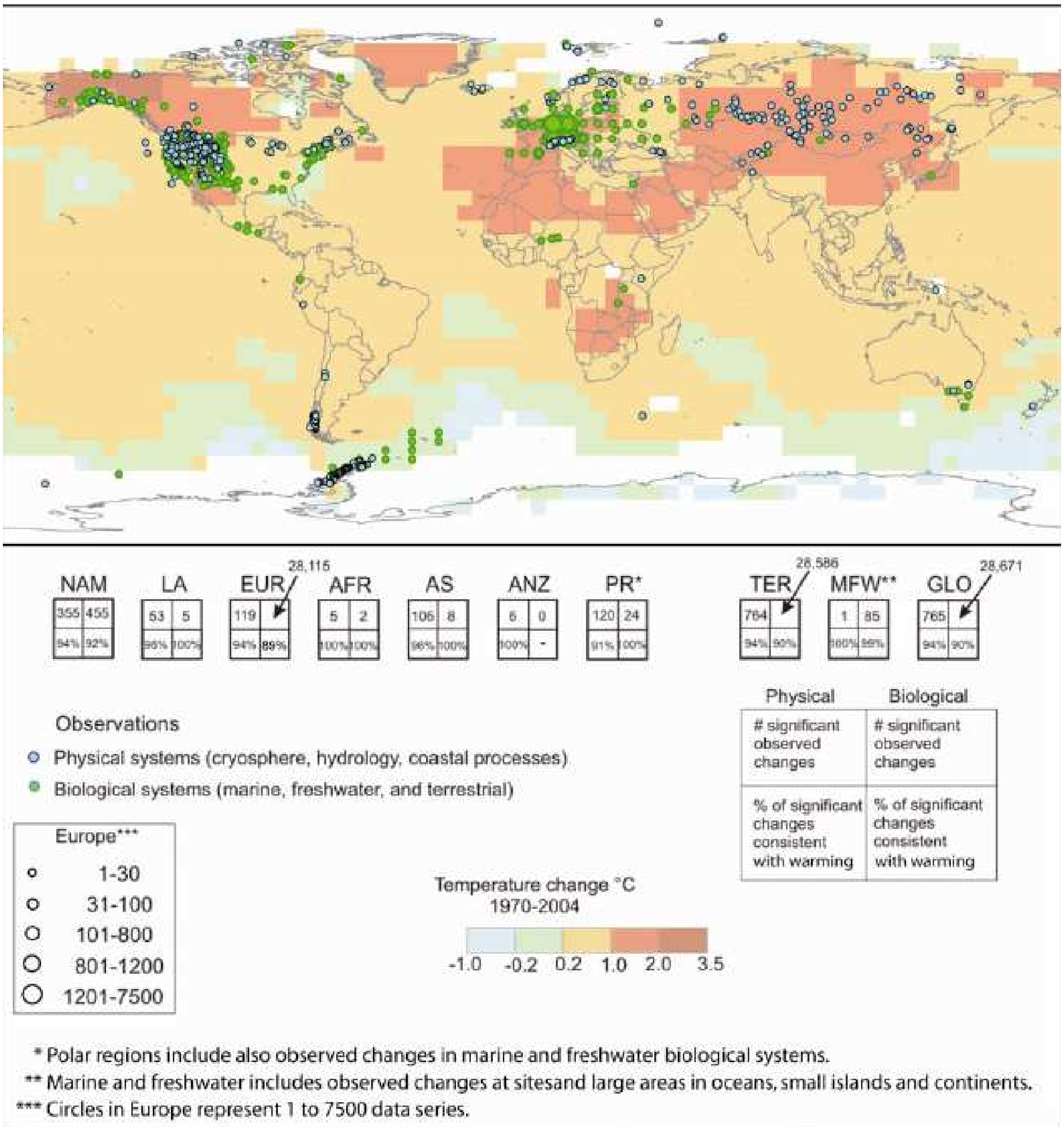
Greenhouse gasses in the atmosphere absorb some of the radiation emitted by Earth, and in turn emit radiation into space. The energy emitted from the gas is connected to temperature described by the Stefan-Boltzmann law given in equation 2-1. T_s is the surface temperature in Kelvin, ε is the emission rate ($0<\varepsilon<1$) and σ is the Stefan-Boltzmann constant $5,67 * 10^{-8}\ W/m^2\ K^4$. The emission rate describes how "efficient" the object emits heat relative to a blackbody, which emits "perfectly".

$$E = \varepsilon\sigma T_s \tag{2-1}$$

Since both the emissivity and absorbability depends on temperature, this could explain the blanket effect. The atmosphere is divided into layers. The lower layer, constituting for about three quarters of the atmosphere, is called the troposphere. In the troposphere, convection is the main source of heat transportation, resulting in a temperature drop of about 6°C per kilometre. Warm air rises and is cooled, while cold air descends and is heated, creating a convective equilibrium. On average the radiation emitted from Earth originates from 6 km altitude. Thus, the temperature of the gasses when emitting heat is lower then when absorbing heat; providing the blanket effect mentioned earlier. "Thickening" the blanket would cause the temperature of the atmosphere to rise because the increase in mass. A doubled carbon dioxide content would, in absence of other effects, increase the temperature by 1,2°C [Houghton, 2004].

2.2 Consequences of Global Warming

IPCC's second report on global warming was released in April 2007. It concludes: *"Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases."*[IPCC, 2007a]. Concerning ice, snow and permafrost areas there is high confidence that the increased emissions has caused enlargement and increased numbers of glacial lakes, increased ground instability in permafrost regions and changes in Arctic and Antarctic ecosystems. There is also high confidence that the hydrological systems are affected shown in increased run-off and earlier spring peak discharge in many glacier- and snow-fed rivers and warming of lakes and rivers in many regions. There is a very high confidence that recent warming is affecting biological systems such as earlier timing of spring events and poleward and upward shifts in ranges in plant and animal species. Concerning marine and freshwater based biological systems, there is high confidence that rising water temperature, changes in ice cover, salinity, oxygen levels and circulation have occurred. This has led to shifts in ranges and changes in algal, plankton and fish abundance in high latitude oceans, an increase in algal and zooplankton abundance in high-latitude and high-altitude lakes and changes in range and earlier migration of fish in rivers [IPCC, 2007a]. Figure 2-2 shows reported changes in biological and physical systems and surface temperature in the period 1970-2004 based on observations across the globe. As the figure shows, most of the observations originate from Europe and Northern America, which means that more observations in Africa, Asia and Latin America should be conducted to achieve global data.



* Polar regions include also observed changes in marine and freshwater biological systems.
** Marine and freshwater includes observed changes at sitesand large areas in oceans, small islands and continents.
*** Circles in Europe represent 1 to 7500 data series.

Figure 2-2: Changes in physical and biological systems and surface temperature 1970-2004 [IPCC, 2007a]

2.2.1 Future Consequences of Global Warming

As the previous chapter showed, several changes have already been observed. The second report from IPCC also projects future changes in several areas. Impacts are often connected to changes in precipitation and other climate variables in addition to temperature, sea level and concentrations of atmospheric carbon dioxide. The magnitude and timing of impacts will vary with the amount and timing of climate change and, in some cases, the capacity to adapt. The report covers several areas not presented in this paper, which will only cover changes in Europe, and some specific changes in Norway. Climate change is expected to magnify regional differences in Europe’s natural resources and assets. Storminess and sea-level rise will lead to increased risk of inland flash floods, more frequent coastal flooding and increased erosion. In Southern Europe higher temperatures and drought will reduce water availability, hydropower potential and crop productivity. It is also projected to increase health risks due to heat waves and the frequency of wildfires. In Central and Eastern Europe high water stress is expected due to a decrease in summer precipitation. Health risks due to heat waves are projected to increase. Forest productivity is expected to decline and the frequency of peat land fires to increase. In Northern Europe, climate change will have a mixed effect. Reduced demand for heating, increased crop yields and increased forest growth are positive consequences of global warming. However, as climate change continues, its negative impacts (including more frequent winter floods, endangered ecosystems and increasing ground instability) are likely to outweigh its benefits [IPCC, 2007a].

Precipitation in Norway will increase, especially in the western and northern parts. Calculations show that precipitation in the period 2030-2050 will increase by 20 per cent in these areas in comparison to 1980-2000. Temperature is expected to rise, mostly in winter and in the northern parts. Both single species and whole eco-systems will be affected. Some species could experience a decrease in living territory, both concerning latitude and altitude. Even though crop yields will increase, the higher temperature and precipitation provides better living conditions for vermin. The more intense agriculture could also lead to erosion and lack of nutrients in the soil.

2.3 Reducing the Emissions and Global Warming

May 4th this year UN's Intergovernmental Panel on Climate Change (IPCC) released third part of their fourth report on climate change. It deals with trends in society's emissions of climate gasses and how they could be reduced. It concludes with a high degree of certainty that global emissions have grown since pre-industrial times with a 70 per cent increase between 1970 and 2004, and that emissions will continue to rise in the coming decades [IPCC, 2007]. As Figure 2-3 shows, emissions are strongly coupled with standard of living and population. The report states there is "*substantial economic potential for the mitigation of global GHG emissions over the coming decades, which could offset the projected growth of global emissions or reduce emissions below current levels.*" [IPCC, 2007]

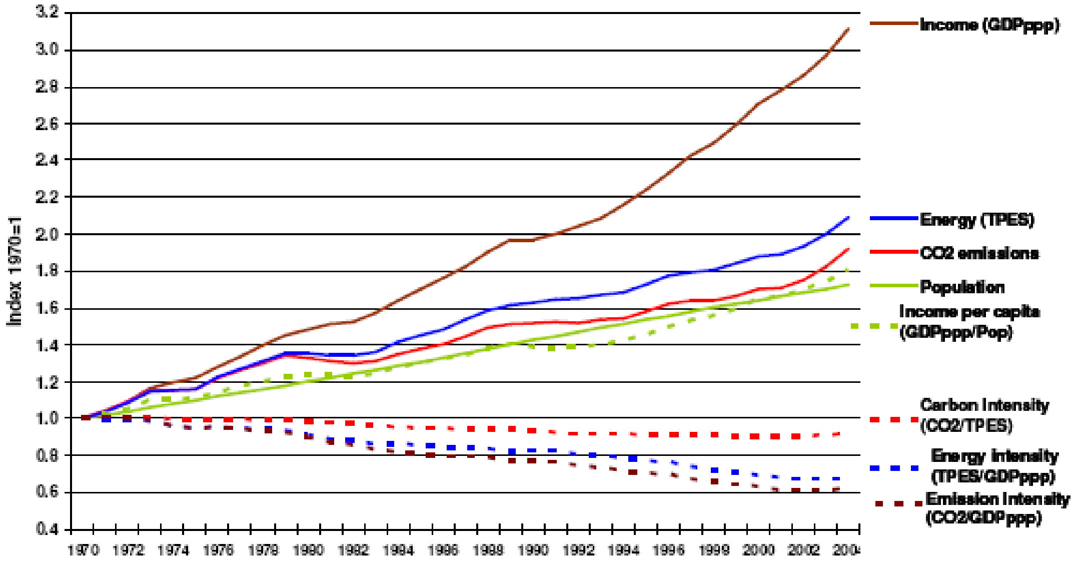


Figure 2-3: Relative development of several factors [IPCC, 2007]

In Norway a commission has been working with the same problems as the IPCC, but concentrated on Norway. The Norwegian Commission on Low Emissions main task was to elucidate how Norway could achieve significant reductions in its greenhouse gas emissions. The commission developed scenarios on how a "low emission society" could be developed within fifty years, where the national emissions are reduced with 50-80 per cent within 2050. The report concluded that *"Norway […] easily [could] reduce its emissions by two thirds within 2050. It doesn't even have to be expensive if we start right now and reduce emissions gradually"* [CICERO, 2005]. Their measures focused on large single source emissions and also created two basic measurements for reducing the emissions. The sectors in which the large emissions have been divided into, and the relative reductions, could be seen in Figure 2-4. The first basic measurement is to implement a national effort for distributing climate information. The information must be factual and well presented about the problem and what could be done. The second basic measurement is a long-term commitment to develop climate friendly technologies. The report mentions technologies such as CO_2-capture and storage, wind power (especially at sea), pellet- and clean burning technologies, bio-fuels, solar panels, hydrogen technology, heat pumps and low emission vessels [Lavutslipp, 2006].

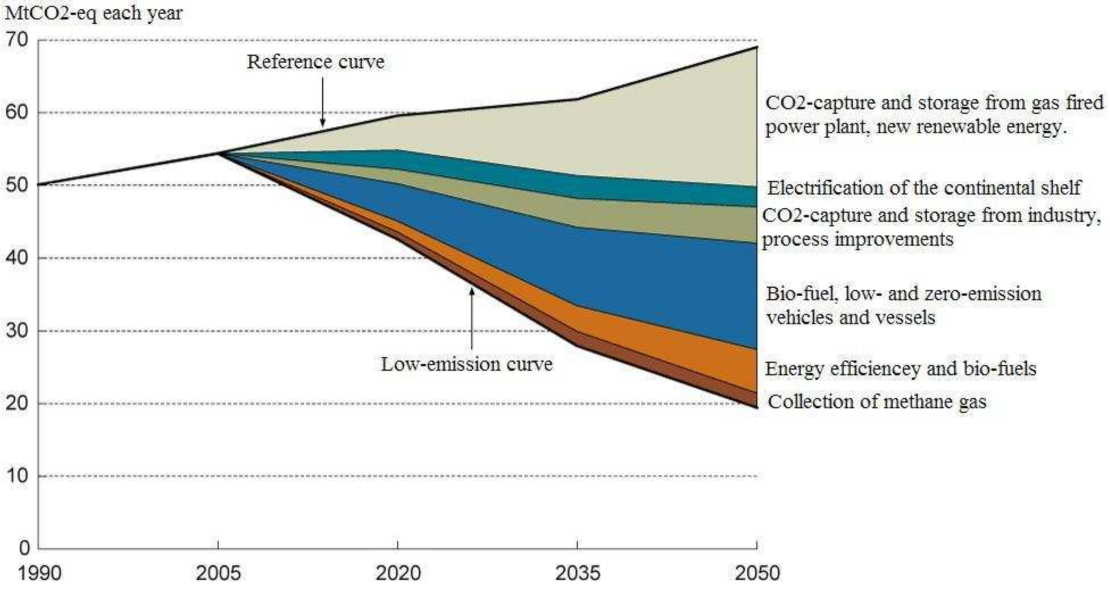


Figure 2-4: Emission reductions in Norway [Lavutslipp, 2006]

This short coverage of global warming shows that the consequences could be severe for all nations on Earth, and that they will affect several different areas of society. It also shows that measures could be taken to reduce the consequences and that they are feasible with small or no economic losses.

3 Industrial Ecology and Eco-Industrial Parks

In the 1950s ecologist began evaluating emissions from industries and their impact on the environment, the so-called “end of pipe”-approach. They studied one system’s effect on another; the industrial system’s effects on the natural system. The field of industrial ecology explores the contrary; the industrial systems also behave like eco-systems, and as part of it [Erkman, 1997]. The term was first used in about 1970, but did not manifest itself before the early 1990. At that time the focus on environmental subjects was evolving, especially after the release of the UN report “Our Common Future”, often referred to as the Brundtland Report, in 1987 [Bæredygtig Udvikling, 2007]. It produced one of the most widely quoted definitions in recent history. It defined sustainable development as *“[...] development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”* [Wikipedia, 2007]. The report led to the conference in Rio and the development of Local Agenda 21. In the light of the new focus on environmental issues, one saw that the old way of solving environmental problems were not sufficient for the complex problems that the world faced. Thus the “forgotten” concept of industrial ecology started evolving. There is not one set definition for industrial ecology, but often used is Robert White’s definition from 1994:

“*Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effect of these flows on the environment, and of the influence of economic, political, regulatory and social factors on the flow, use and transformation of resources. The objective of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities. This integration, an ongoing process, is necessary if we are to address current and future environmental concerns.”* [Industrial Ecology NTNU, 2007].

The superior theme of the industrial ecology field is a holistic approach. Moving from end-of-pipe and single unit thought to cradle-to-grave and systems perspective is a whole new way of thinking. To better understand the concept of industrial ecology, one could break up the definition from White.

[Study of the flows of materials and energy in industrial and consumer activities.]
The analysis of large and complex systems requires quantitative data of flows connected to the system. The problem at hand decides what level of aggregation should be used. Industrial ecology is often said to act on three levels; firm level, between firms and regional/national. On any level the system must obey the rules of physics, and with that as a background flows could be quantified and systemized for further analysis. Tools developed in industrial ecology concerning this subject include material flow analysis (MFA), substance flow analysis (SFA) and life cycle assessment (LCA).

[The effect of these flows on the environment]
The effect of the flows is based on environmental categories for different substances. Following the flow analysis the fate of compounds is found. Using biological, chemical and physical data a system for environmental impacts has been developed. It is based on different potential environmental effects; e.g. global warming, toxicity and ozone depletion potential.

[The influence of economic, political, regulatory and social factors on the flow, use and transformation of resources]
This is where industrial ecology particularly stands out from similar methods. While based on typical engineering evaluations, industrial ecology tools also include effects of economic or social character. Strategies for implementing the new ideas are also part of industrial ecology. The flow analysis tool LCA could for instance analyze monetary flows, a tool called life cycle cost-analysis (LCC).

The main focus of industrial ecology since the concept was revived has been development of tools such as LCA, MFA and EIPs. All tools based on the metaphor of ecological flows. Figure 3-1 shows the basic concepts of industrial ecology. As an environmental field the goal is to reduce the use of virgin materials and the production of waste. The tools of industrial ecology are created for analyzing the flows and identifying bottlenecks and areas where measurements could be taken. As the figure shows there are relations between every actor in society, as in nature's metabolism.

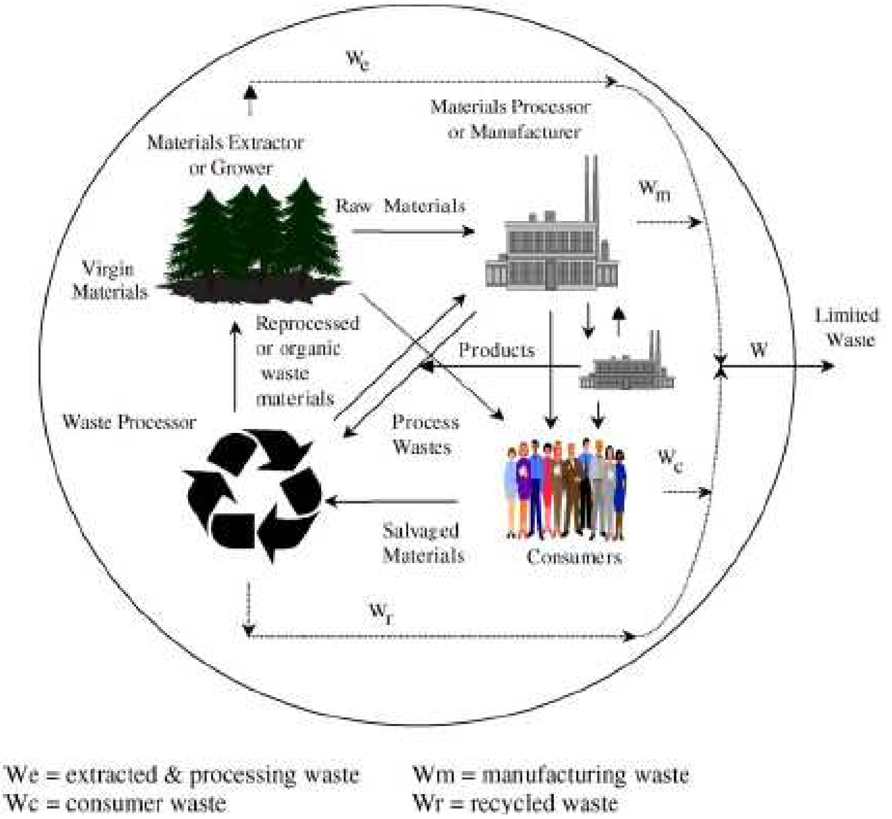


Figure 3-1: Basic concepts of industrial ecology [Roberts, 2004]

Industrial ecology seem to have branched into two directions; eco-industrial parks and dematerialization [Erkman, 1997]. The dematerialization relates to the development of concepts and strategies for the optimization of the flows of materials within the economy, which is largely based on technological evolution. Although not a new concept, dematerialization has attracted new interest and is seen as a positive trend and a desirable strategy [Herman, Ardekani and Ausubèl, 1990]. The second branch, eco-industrial parks will be thoroughly covered in the following chapter.

3.1 Eco-Industrial Parks

Since the growing interest for industrial ecology in the early 1990s several tools and concepts have been developed. One of the concepts evolved was eco-industrial parks. There are many definitions of eco-industrial parks, also called industrial symbiosis. Some have strict requirements that must be fulfilled before one could rightly call it an eco-park. Others lean more on the conceptual approach, to utilize available resources in the best manner. But as Desrochers [2004] states; the use of waste as a resource is not a new way of thinking. Throughout time several examples show that societies have used waste from other productions to make their product, e.g.; using bones from slaughterers to manufacture tools or ornaments. The concept is easily translated to good economy. Instead of paying someone to remove your waste, you get paid to deliver your waste to someone that can use it. A widely used definition is the President's Council for Sustainable Development [1996] defention: An eco-industrial park is *"[a] community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community.* It is a win-win-win situation that shows that focus on environment is not necessarily in contrast to good company economics.

The best known example of industrial symbiosis is Kalundborg in Denmark. Developed from the 1970s, it has naturally developed from several different industries to the worlds most acknowledged eco-park. From the 30 year expansion of Kalundborg some guidelines have been developed.

- The companies must fit each other – residual products from one industry must take the place of another's raw material. Thus, diversity in the local industries is important.
- The companies must be located near each other – expenses become larger with increased distances. Also exchange of energy is prone to larger losses and expenses. Experience from Kalundborg shows that this is single most important factor when it comes to energy exchange.
- There must be openness between the companies – Kalundborg is based on openness, communication and trust between the involved companies. [Industrial Symbiosis, 2006]

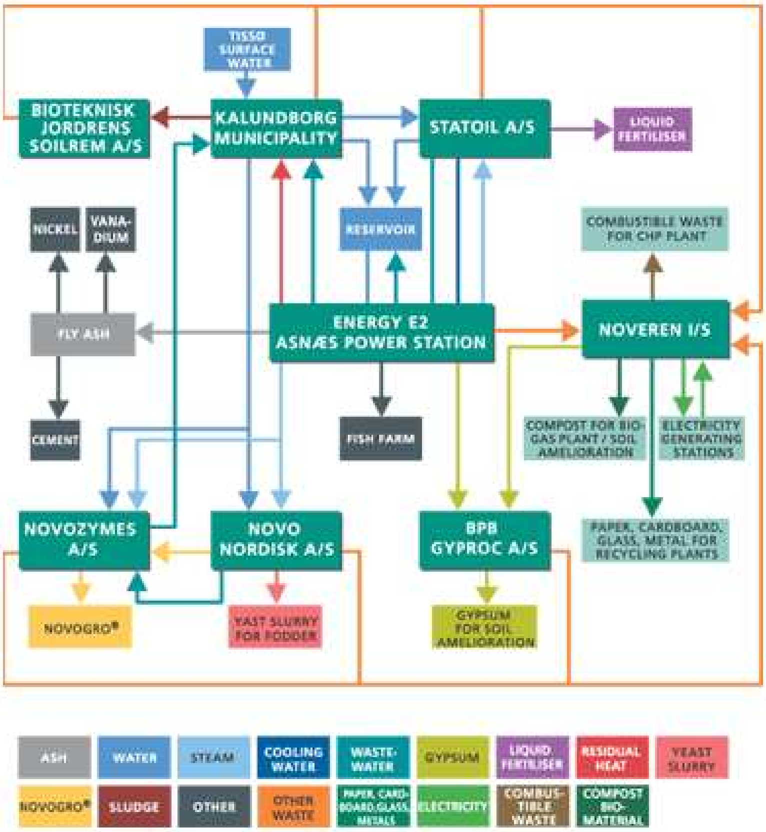


Figure 3-2: Kalundborg symbiosys [Industrial Symbiosis, 2006]

Kalundborg has developed through 30 years, the drive being the market forces. The success and experience of the small municipality in Denmark has triggered the interest for eco-parks all over the world. Several countries have governmental plans for developing similar symbiosis in their own countries. Desrochers [2004] argues that this approach is a total misunderstanding of the experience from Kalundborg. That design teams and governmental institutions have underestimated the powerful role the market has had on the development of Kalundborg. On the other hand, Hawken [1993] states: *"Imagine what a team of designers could come up with if they were to start from scratch, locating and specifying industries and factories that had potentially synergistic and symbiotic relationships."* These opposing statements illustrates that, even if they agree on the usefulness of eco-parks, the manner of which they develop is seen in different context. This shows the complexity of the problem in developing successful industrial symbiosis.

The points above describe guidelines drawn from the experience of Kalundborg and shows that there are different views on how to develop new eco-parks. Some researchers have tried to develop tools to evolve eco-parks. By defining necessary requirements and methods to develop eco-parks the researchers hope to help developers to construct successful eco-parks in the future. Lowe [2001] has defined a set of strategies for designing EIPs.

Integration into natural systems – Select your site using an assessment of ecological carrying capacity and design within the limits it defines. Minimize local environmental impacts by integrating the EIP into local landscape, hydrologic setting, and ecosystem. Minimize contributions to global environmental impacts, e.g. greenhouse gas emissions.

Energy Systems – Maximize energy efficiency through facility design or rehabilitation, co-generation, energy cascading and other means. Achieve higher efficiency through inter-planty energy flows. Use renewable resources extensively.

Material flows and waste management for the whole site – Emphasize cleaner production and pollution prevention, especially with toxic substances. Seek maximum re-use and recycling of materials among EIP businesses. Reduce toxic material risks through material substitutions and integrated site-level waste treatment. Link the EIP tenants to companies in the surrounding region as costumers and generators of usable by-products via resource exchanges and recycling networks.

Water – Design water flows to conserve resources and reduce pollution through strategies similar to those described for energy and materials.

Effective EIP management – In addition to standard park service, recruitment and maintenance functions, park management also:

- Maintains the mix of companies needed to use each others' by-products as companies change over time;
- Supports improvement in environmental performance for individual companies and the park as a whole;
- Operates a site-wide information system that supports inter-company communications, informs members of local environmental conditions, and provides feedback on EIP performance.

Construction/rehabilitation – With new construction or rehabilitation of existing buildings, follow best environmental practices in materials selection and building technology. These include recycling or reuse of materials and consideration of lifecycle environmental implications of materials and technologies-

Integration in the host community – Seek to benefit local economy and social systems through training and education programs, community business development, building of employee housing and collaborative urban planning.

Even though these strategies were developed for developing countries in Asia, most of them are still very valid for developing EIPs everywhere. The cooperation and good integration with the nearby areas should not be underestimated. Dialog with local authorities and inhabitants is important to achieve good integration of the EIP in the municipality.

3.1.1 EIPs as a Tool

In recent years industrial ecology, and the tools associated with the field, has gotten more attention. Several papers have been published, showing the use of tools within the field as solutions to the immense environmental challenges the Earth is experiencing. In the wake of the almost euphoric state, researchers have begun to look into how the theory has been implemented in practical solutions. This is also the case for EIPs. In literature covering industrial ecology several high profile EIPs are mentioned. For example the four US sites set-up by the President's Council for Sustainable Development at Cape Charles, Chattanooga, Brownsville and Baltimore. The only one actually developed was Brownsville, but has now abandoned the eco-industrial theme [Gibbs and Deutz, 2007]. Korhonen [2004] even argues that Kalundborg, often regarded as the prime example of industrial symbiosis in action, relies on non-renewable fossil fuels and produces CO_2 emissions and is therefore not an eco-industrial park. Acknowledging that industrial ecology is a relatively new field and that taking the tool of industrial symbiosis from theory to action, researchers describe areas that limit the transition. Heeres, Vermueulen and de Walle [2004] suggest barriers to develop the exchanges could be;

- Technical – where an exchange is technically not feasible
- Economical – where exchanges are economically unsound or risky
- Informational – where the appropriate people do not have the relevant information at the right time
- Organisational – where exchanges may not fit with corporate structures
- Regulatory or legal – where exchanges are not allowed to occur

Gibbs and Deutz [2007] discovered through their literature study and in-depth interviews of several parks that none fulfilled the eco-industrial park ideal, and that most exchanges where either in the planning stage or that the environmental and economic benefits of synergies were not quantified. Peck [2002] argues that one of the reasons the development has slowed or halted is the lack of a specific framework, or a more specific definition. Several models could be used, for instance a system developed or implemented in the ISO14001 system, or a system more like the labelling of products. This will help parks, industry, communities and governmental participants set their goal. This concurs with the conclusions of Heeres et al. [2004] after evaluating why the Dutch EIPs in their research was more successful then the American ones evaluated. The difference did not lie in the problem of *what* defines an EIP, but in the process of *how* they develop. And the importance of each different factor, whether driving or limiting, will vary depending on which geographical, social, political, environmental, economic and institutional context the EIPs are being developed [Tudor, Adam and Bates, 2007].

3.1.2 Economy and Environment in EIPs – two Case Studies

Although several authors, as shown in the last chapter, point out why parks are not fulfilling the eco-park ideal, development of such parks still continues. The next chapters present three EIPs, and examples of both economic and environmental gains following symbiotic systems. The two first are newly investigated parks in China and Australia, while the last is based on the first in-depth research focused on achieving quantitative results on economic and environmental benefits.

3.1.2.1 The Guitang Group

Based around a sugar refinery built in 1956, the Guitang Group (GG) has developed immensely in the last five decades. Expansion of the area, introducing new facilities and keeping close relations with suppliers and local government has always been sought after by the group. Their ISO9001 certification from 1998 and their strive to fulfil the requirements for the ISO14001 certification shows that both quality and environmental goals are important for the GG management [Zhu, Lowe, Wei and Barnes, 2007]. At the turn of the millennium GG was acclaimed by the State Environmental Protection Administration of China (SEPA) for its good economic results and continence use of environmental resources. And the year after this recognition the GG was approved as an EIP demonstration park [SEPA, 2004].

Figure 3-3 shows the exchange network at the Guitang Group. In its beginning it was based around the sugar refinery and an alcohol plant that utilizes the molasses by-product from the production of sugar. Throughout the years the group added three paper mills using bagasse, a fiber residue from the crushing and grinding of raw sugarcane, as raw material. This opened up new lines of business caused by higher quality and reduced environmental burdens. The park is mainly divided into two main chains, the sugar chain (containing the originally conceived sugar refinery and the alcohol plant) and the paper chain (containing the pulp and paper mills). Processes are also applied to reduce the amount of residual waste.

The sugar chain produces sugar, alcohol, cement and fertilizer. There are mainly two ways of producing sugar, either by carbonation or phosphatation. The latter being most common, and the first providing higher quality refined sugar. But the carbonation also produces a waste problem, as the residue can not be used directly as fertilizer as in the other process. In the GG the mud-waste created by the process is used as an input into the area's cement production. The residues from alcohol production (remains of the molasses), which formally would have been a waste problem is now used as an input to produce fertilizer for the sugarcane plantations.

The paper chain is based on the input of bagasse, a remainder of the sugar mill. Sixty per cent of the bagasse has fibres long enough to be used in the paper production. The shorter fibres are used to produce energy in the co-generation unit. To produce paper from the bagasse, the pulper needs input of alkalis. The alkali will be part of the residue "black liquor" in large amounts, and the GG has built an alkali recovery plant to recycle the alkali and to produce white sludge used in the cement production. Large streams of fibres and water, called white sludge, is recycled and recovered from the paper mills through an own treatment plant.

There are little directly reported environmental and economical benefits from the development of the industrial symbiosis at Guitang. However, Zhu et al. [2007] presents some important positive aspects in both areas. Coal is partly substituted by pith which has half the SO_2-emissions, and zero CO_2-emissions if one regards biomass as CO_2-neutral. By choosing to produce the better quality sugar, by carbonation, the plant created a waste problem and raised costs. But by viewing the waste as a resource for the cement factory offset these extra costs; and the higher quality sugar provided the company with 10 per cent higher premiums. The investment in the alkali recovery plant halved the cost of alkali for the pulp plant, and lowered production costs. The external sugar refineries previously (before 2000) produced 300,000 tonnes of molasses and 200,000 tonnes of bagasse in need of disposal which is now used as inputs in the alcohol and paper production respectively.

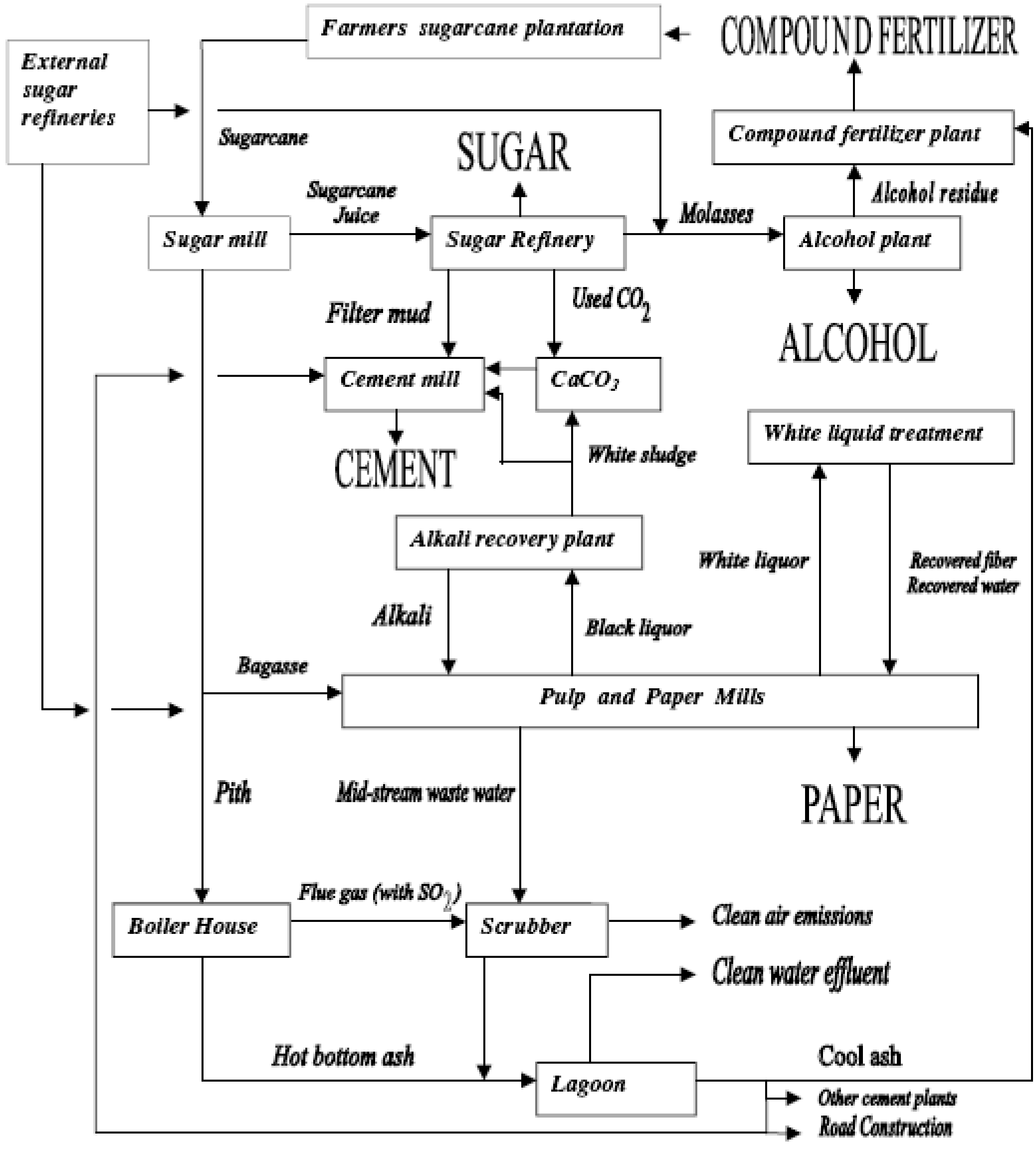


Figure 3-3: Guitang Group Exchange Network [Zhu et al., 2007]

Even though the symbiosis seems to be a good example of a win-win situation there are several challenges for the group, global and domestic. With China joining the WTO and gradual privatization of its market, the conditions change. Where the Chinese government earlier could protect domestic industry with quotas and tariffs, their expansion into the world market has caused tariffs to drop and quotas to rise. Also the area's dependence on sugar production could be a challenge. Years with low crops, a maximum area available for cultivating sugarcanes and farmers changing their production to more profitable products are all domestic factors that could cause problems for the GG [Zhu et al., 2007].

3.1.2.2 Kwinana Industrial Area

The Kwinana industry area was established in the 50s in Australia's most sparsely populated state, Western Australia. The area has large quantities of natural resources which are reflected through the density of heavy process industries. Several mineral plants producing alumina, nickel, titanium, cement and iron exist. A massive oil-refinery producing 135,000 barrels/day is also situated there. And a vast range of chemical plants as well as several energy producing installations constitutes the area. All these facilities are connected to a deep water port shows that the area is designed as a large industrial area from the beginning. Several of the factories located in the area produce raw material for other production facilities [van Beers, Corder, Bossilkov and van Berkel, 2007]

In 1991 the core industries in the area formed Kwinana Industry Council (KIC) to cooperate in monitoring air and water emissions from the area. To study the effect of the industrial area, both economically and socially, the council requested a regional economic impact study. The last one is from 2001 [SKM, 2002] also includes analysis of the principal energy and material flows. The report revealed a total of 106 interactions between companies; almost triple the amount of interactions only ten years before. This lead to the initiation of the Kwinana Industries Synergies Project which later merged with Centre of Excellence in Cleaner Production at the Curtin University of Technology. The last updated report from the area showed a total of forty-seven synergies in place, including 32 by-products as seen in Figure 3-4 and 15 utility, shown in Figure 3-5 [van Beers, Bossilkov and van Berkel, 2005].

Though it is too comprehensive to explain every synergy in the area, some examples of by-product and utility synergies will be presented.

Examples of by-product synergies:

- Pigment plant supplying hydrochloric acid to chemical manufacturer to produce ammonium chloride
- Chemical plant supplying food grade carbon dioxide to utility gas provider
- Chemical plant supplying gypsum for residue area amelioration at alumina refinery
- Oil refinery providing hydrogen for city bus trail
- Chemical plant supplying carbon dioxide for residue neutralization at alumina refinery

Examples of utility synergies:

- Reuse of recycled effluent from Kwinana Waste Water Treatment Plant (WTTP) at the alumina refinery
- Cogeneration plant at oil refinery
- Cogeneration at titanium dioxide pigment plant
- Chemical plant supplying water to pigment plant
- Artificial wetland treatment at chemical plant

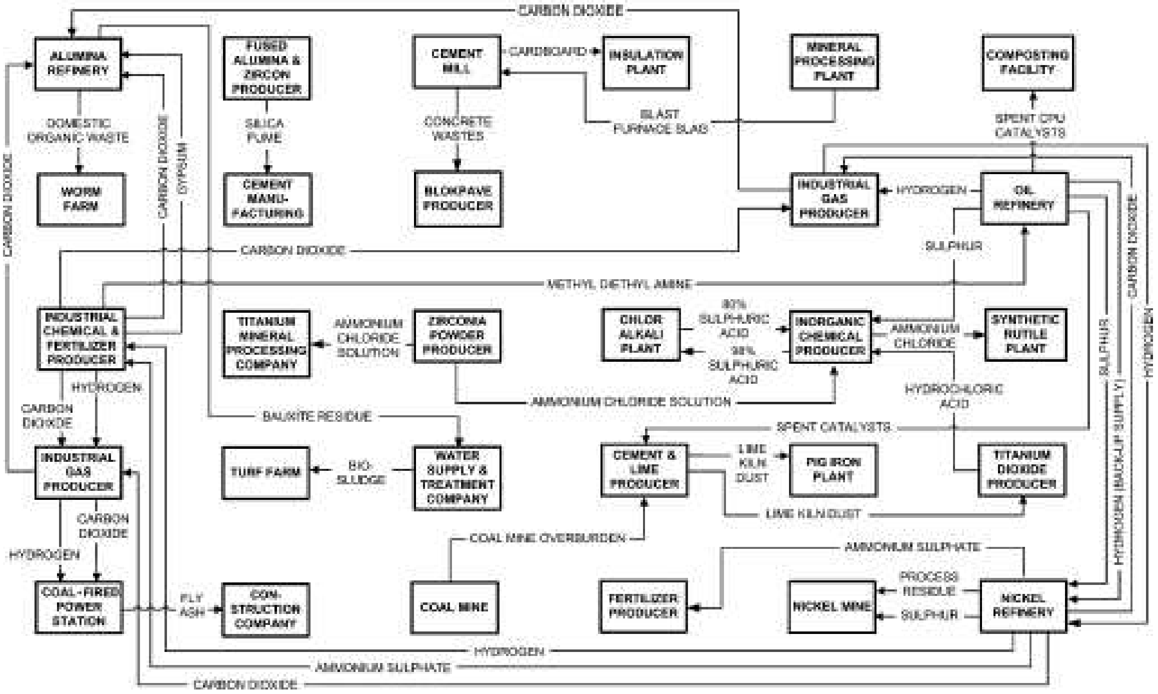


Figure 3-4: By-product synergies at Kwinana [van Beers et al., 2007]

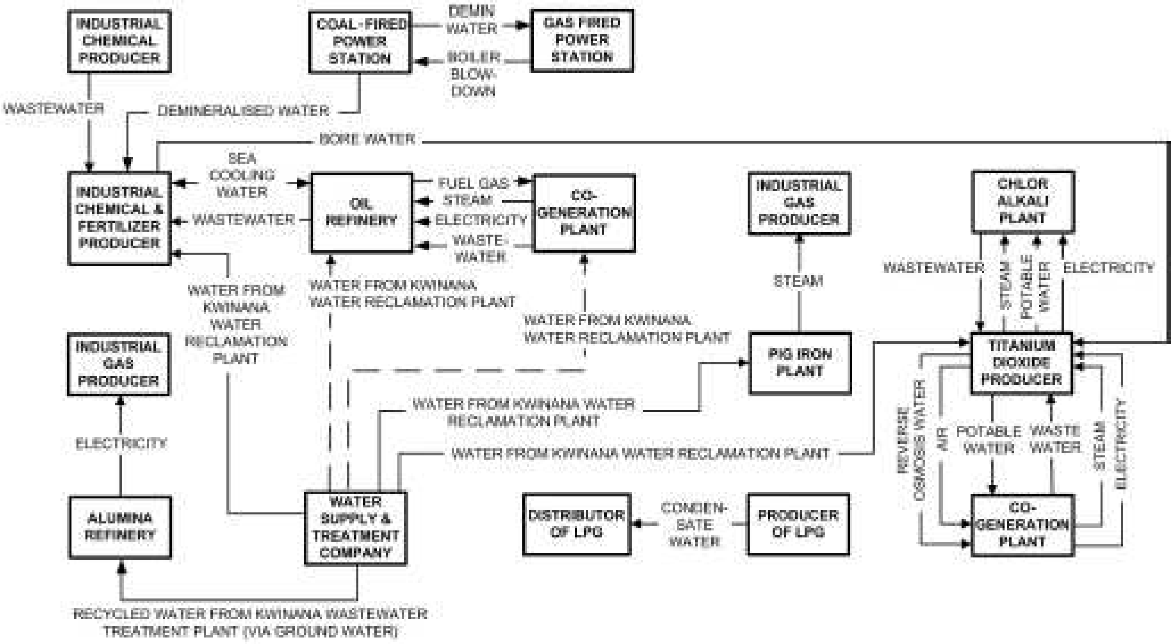


Figure 3-5: Utility synergies at Kwinana [van Beers et al., 2007]

As in the case study from China, little quantitive data is avaliable form the Kwinana synergies. In Alcoa's synergy effect, using carbon dioxide to reduce the alkalinity of its bauxite residue, about 70,000 tons of CO_2 is not emitted to the atmosphere. Also, the substitution from the boiler producing steam for the refinery to steam being produced in the cogeneration plant saves 170,000 tons of CO_2 emissions annually [van Beers et al., 2005].

3.1.3 Economy and Environment in Kalundborg

As the case presentations of the Guitang Group and Kwinana EIPs show, there is little or no quantitative data on either economical or environmental benefits from the industrial symbiosis. In fact, very little literature has been produced focusing on this area. In 2006, Brings Jacobsen published a paper concerning this area of interest on the frequently cited Kalundborg. This follow chapter presents the main results of this paper.

3.1.3.1 Analysis Method and System Description

The financial analysis in the paper is based in the water system and steam/heat exchange at Kalundborg. Figure 3-6 shows the system between the refinery, power plant and the Novo group. As the figure shows, there are three sources of water for Kalundborg; sea water, ground water and surface water. Environmental effects of the water exchange are based on the ability to reduce the use of high quality water using substitution and water cascading. "*The cascade chain is a theoretical notion which integrates concepts of resource economy and sustainability into an operational framework for determining the efficiency and appropriateness of a given resource exploitation in a given context.*" [Sirkin and ten Houten, 1994, p. 3].

For the steam/heat exchange the environmental effects are analyzed in terms of the cogeneration effect and the net reduction of three environmental gasses compared to a hypothetical stand-alone production. In economical bearings the exchanges are evaluated in regards to investments and direct and indirect results of product streams.

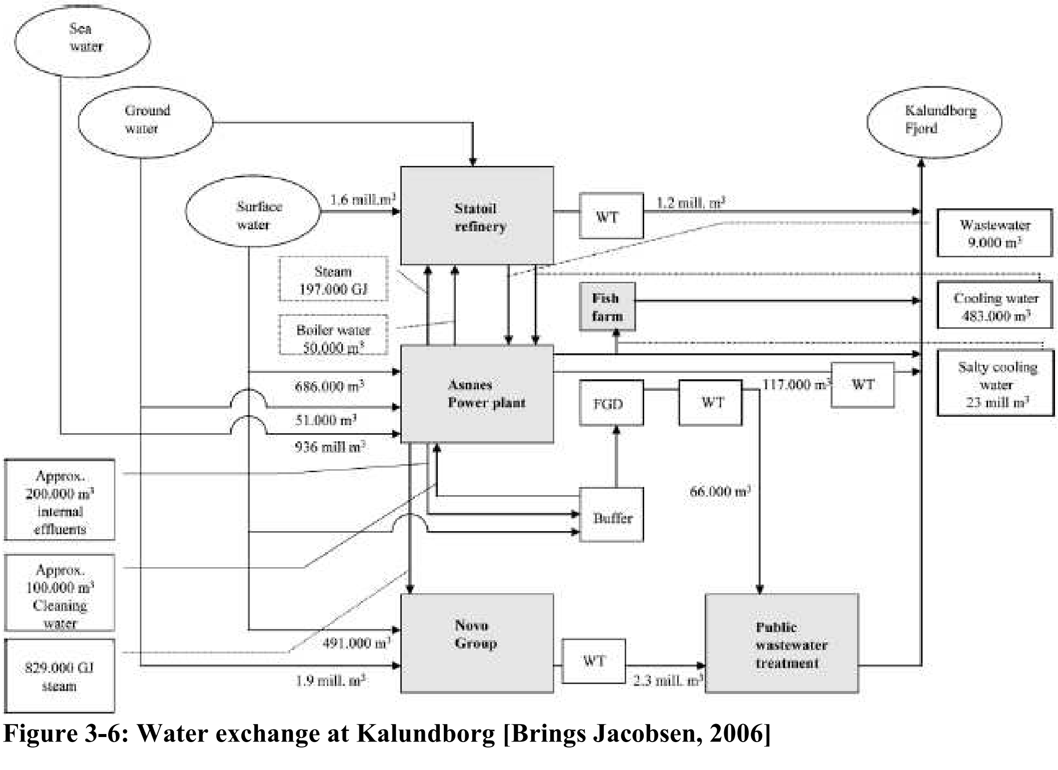


Figure 3-6: Water exchange at Kalundborg [Brings Jacobsen, 2006]

Deficit of groundwater was the factor that triggered the search for other sources of water as the plants expanded over the years. In 1961 the groundwater was replaced by surface water in the most water-consuming industries. Inter-firm optimization of water using operations started as off 1975. From 1997 processes that upgrade surface water to drinking water was installed, and the area started importing groundwater form nearby regions. The compilation of these three different strategies has created a diverse water supply system. The development has given significant changes in the water use, with a doubling of the use of surface water. And as seen in Figure 3-6 the Asnæs power plant is the centre of most of the symbiotic streams. Thus the development of water use at the plant is interesting. Figure 3-7 shows the water usage from 1990-2002, and clearly shows that groundwater has been substituted with other sources of water. And due to new installations such as boilers and water-based sulphur cleaners, prognoses for the annual use of water at the plant nearly tripled (from 1,069 to 3 mill m^3) in 12 years. Instead, several measures turned the 3 million m^3 of high-quality water into 1,2 million m^3 of low-quality water.

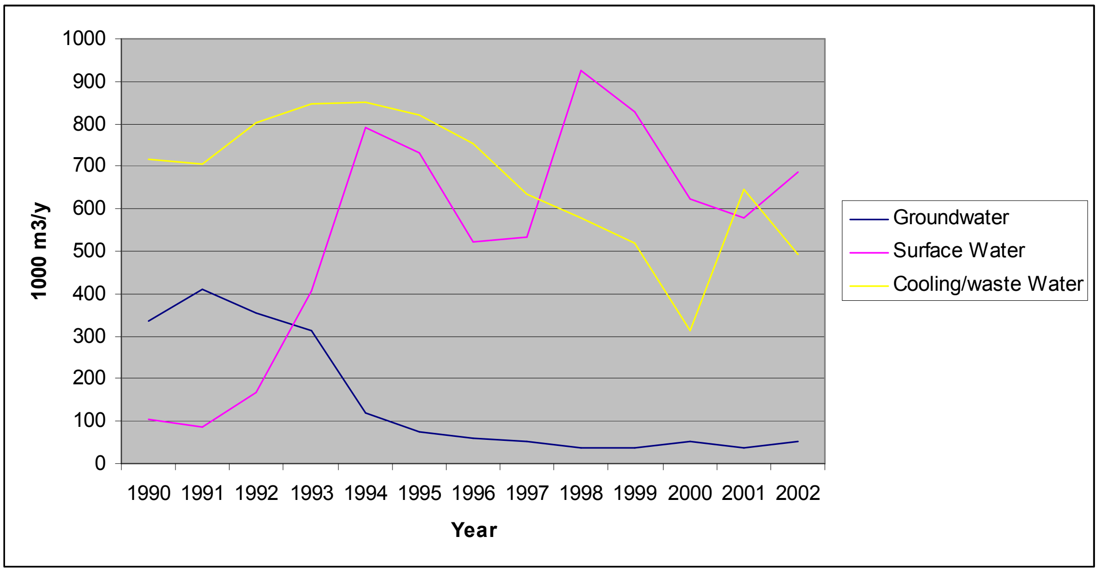


Figure 3-7: Water consumption at Asnæs power plant

For both the power plant and the refinery the symbiotic exchange of water is of great importance. More then 95 per cent of the power plant's and 98 per cent of the refinery's water input comes from streams symbiotic in nature. Although only twenty per cent of the water input for the Novo facility is symbiotic, more then fifty per cent of the energy required originates from the symbiotic heat/steam flows.

3.1.3.2 Quantitative Results

Replacement of Fresh Groundwater with Surface Water

The power plant and the other symbiotic partners use surface water and upgrades it so that it could be used in boilers, producing steam. This reduces the extraction of ground water by 686,000 m^3 annually. Based on the price difference between ground- and surface water, this replacement led to an annual saving of $960,000. With an investment of about $4,400,000 the investment had a payback of less than five years.

Replacement of Surface Water with Cooling Water
Whereas the intake of surface water is based on utility sharing, the delivery of cooling water to the power plant from the refinery is based on substitution and cascading. The power plant uses cooling water instead of surface water. This means that more surface water is available to the refinery, thus replacing groundwater. From 1990 to 2002 this has saved 7,6 million m^3 of surface water. Based on a investment of about $253,000, this exchange provided an annual saving for both the refinery and the power plant of $228,000.

Replacement of Surface Water and Cooling Water with Wastewater
Some of the cooling water and surface water at the power plant is replaced by wastewater from the refinery. Although decreasing each year (only 9,000 m^3 in 2002) a total of 1,1 million m^3 has been delivered from 1992-2002, giving a direct economic gain for the power plant of about $568,000. The decrease was a result of the instalment of an internal recycling program.

Steam and Heat Cogeneration at the Asnæs Power Plant
Steam is produced as a by-product of electricity production at the power plant and delivered to neighbouring facilities and as heat in the district heating system. Of three possible solutions for providing steam to their process, the Novo facility's study showed that steam from the cogeneration plant was most viable both economic and environmental. Because of difficulty to obtain historical data, and also large fluctuations in which boilers and what fuels used through a historical perspective, more current data was used for the calculations. In the investigated timeline (1997-2002) the symbiosis reduced 154 Mtons of CO_2 and 389 tons of NO_x compared to steam produced in a stand-alone gas-fired boiler. The chosen boiler at Asnæs and the use of Orimulsion as fuel resulted though in 304 tons of SO_2, while natural gas releases no sulphur.

Salty Cooling Water from the Power Plant to Fish Farm
The boiler water at the power plant is cooled using salt sea water. The temperature of the cooling water is elevated by 7-8°C and is used in fish farms. 39 TJ of heat is utilized in the fish farm. This is only 2,5 per cent of the total heat discharged with the cooling water. This shows two things; firstly, it means that there is great potential; secondly, it shows that finding applicable areas for low temperature heat is hard. The water results in a fifteen per cent increase in fish production. Only a small investment of 75,000 DKK was made with a payback of less than two years.

3.1.4 Future of Eco-Industrial Parks

Chapter 3.1.1 shows that many researchers in the last years has pointed out that development of EIPs has not been the great success the demagogues and protagonists claimed it would be. Presented as a win-win-win situation the concept seemed logical for engineers, developers and economists. But as parks developed, problems started occurring. The symbiosis was too risky, claimed to high investments and businesses lost flexibility. The immediate success failed to appear. Kalundborg have developed for decades, and the hopes of copying its success in a short time span has failed. Chertow [2000] argues that if parks are to be successful in the future, evolutionary approaches are necessary. Although not the success one hoped for, several examples shows that economic and environmental gains of symbiotic systems occur. The examples from both China and Australia show that their focus on symbiotic relations has provided the industrial area with advantages of both technological and economical character. Even though none of the EIPs actually fulfil the ideal of an eco-park, the symbiotic thought has helped the areas as well as the individual company. As these areas are being developed, new experiences are learned every day, and the field of developing EIPs will evolve.

4 Analytical Tools

4.1 Energy, Exergy and Material Flow Analysis

To understand and analyse the operation of a system one needs to have an understanding of the physics that control it. A detailed analysis of the flows of energy and exergy gives a deeper insight in the system then just input and output data. It could show possibilities and bottlenecks in a system, whether the system is in the design phase or is fully operational. The analysis provides both quantitative and qualitative information. All processes must obey the laws of thermodynamics. The first law of thermodynamics states that all energy in a system is preserved, and is shown in equation 4-1 in rate form.

$$\frac{dE_{CV}}{dt} = \sum_{input} \dot{m}_i (h_i + \frac{1}{2}\vec{V}_i^2 + gz_i) - \sum_{output} \dot{m}_e (h_e + \frac{1}{2}\vec{V}_e^2 + gz_e) + \dot{Q}_{CV} - \dot{W}_{CV} \qquad \textbf{4-1}$$

The left side of the equation denotes the change in energy within the system, set by a given control volume. The control volume sets the border between the system and its surroundings. It could be set arbitrary, depending on what one wants to investigate. The first tier on the right hand side describes the energy from flows entering the system, where m_i gives the mass flow for each input. H_i describes the enthalpy for the given flow. Enthalpy is the sum of internal energy U and the product of pressure p and volume V. The second part of the brackets denotes the kinetic energy of the flow, where V is the velocity of the flow presented as a vector. The last tier in the bracket describes the potential energy of the flow, where g is the gravity constant and z_i is the offset of a given reference frame. The next tier in the equation describes the energy of the flows leaving the system, and the notations refer to the same as for the inflows. Q_{CV} describes the heat transfer between the system and its surroundings. It is defined as positive into the system, and is thus negative if heat loss occurs. The last tier is the work done by the control volume on the surroundings. Figure 4-1 shows a control volume and its surroundings. The surroundings are given by T_0 and P_0.

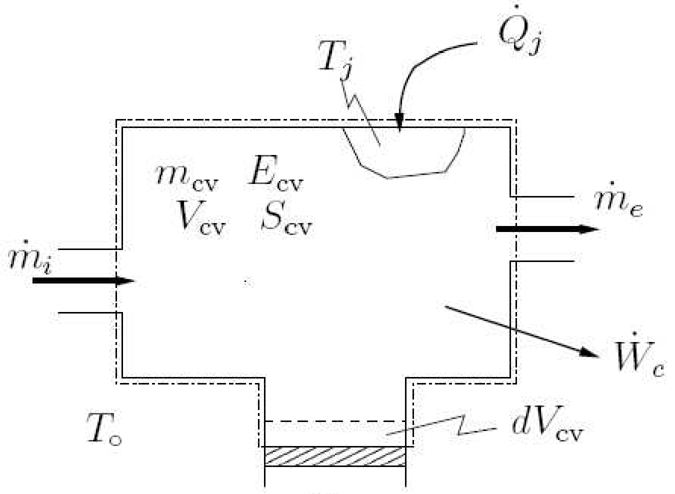


Figure 4-1: A simple control volume [Ertesvåg, 2000]

The tiers in equation 4-1 could be described further to achieve a better understanding of which factors affect the different tiers, but this will not be presented in this paper.

The second law of thermodynamics is somewhat abstract and often hard to comprehend. It basically states that a process, even though the energy is preserved (ref. the first law of thermodynamics), could not endure without inputs. Over time a system will achieve equilibrium, and could not do further work. This is due to the production of entropy, which often is referred to the dispersal of energy. For engineering purposes the entropy balance in equation 4-2 is useful. It shows which factors contribute to the production of entropy.

$$\frac{dS_{CV}}{dt} = \sum_{inputs} \dot{m}_i s_i - \sum_{outputs} \dot{m}_i s_i + \sum_j \int_{T_j} \frac{\delta \dot{Q}_j}{T_j} + \sigma_{CV} \qquad \textbf{4-2}$$

The left side denotes the total entropy change in the control volume over time. The two first tiers on the right hand side describe the change of entropy from flows into and out of the control volume. The third tier describes the production due to heat transfer into the system. If the temperature changes and the heat transfer is a function of this temperature the tier must be integrated for the temperature range. The last tier describes the entropy production within the system. This production is due to internal irreversibility of the control volume.

Availability is a pretty good description of the concept of exergy. Exergy is the maximum amount of work one could achieve. There are two types of exergy, thermo mechanical and chemical exergy. If one think of the dispersal of energy i.e. the production of entropy as a loss of energy quality the combination of the two equations above and mass balance could derive equation 4-3.

$$\frac{dA_{CV}}{dt} = \sum_{inputs} \dot{m}_i a_{f,i} - \sum_{outputs} \dot{m}_i a_{f,i} + \sum_j \int_{T_j} \left(1 - \frac{T_0}{T_j}\right) \delta \dot{Q}_j - \left(\dot{W}_{CV} - p_0 \frac{dV_{CV}}{dt}\right) + T_0 \sigma_{CV} \qquad \textbf{4-3}$$

The left side of the equation denotes the total exergy change in the control volume. The two first tiers of the right side describe the change of exergy from flows into and out of the control volume. The third tier is the exergy change due to heat flows into the system. The fourth is exergy change due to work done, e.g. by a strut or a shaft. The last is the rate of irreversibility, or breakdown of exergy. This equation is based on the assumption that no chemical reactions occur. A similar equation that also includes chemical reactions could be derived. For this paper the exergy in a stream is of substantial interest. The thermo mechanical exergy in a flow is given by equation 4-4. The subscript $_0$ is the enthalpy and entropy for the stream at a given T_0 and P_0, defining the surroundings.

$$a_f = h - h_0 - T_o (s - s_o) + \frac{V^2}{2} + gz \qquad \textbf{4-4}$$

The chemical exergy is a more complicated quantity. Depending on the compound to be examined, a different approach must be taken. Chemical availability is always considered at T_0 and P_0, if a substance is at $T \neq T_0$ and $P \neq P_0$ the change in exergy will be thermo mechanical. For substances present in the atmosphere the chemical availability in molar form is given by equation 4-5.

$$\bar{a}^{ch} = \bar{R}T_0 \ln\left(\frac{1}{y^e}\right) \qquad \textbf{4-5}$$

Where y^e is the mol fraction of the substance in a given environment, and R is the universal gas constant on molar form. For substances reacting with and producing only substances present in the environment another approach must be taken. Consider an arbitrary hydrocarbon that reacts with oxygen. The reaction is given in equation 4-6 and the chemical exergy is described by equation 4-7.

$$C_aH_b + \left(a + \frac{b}{4}\right)O_2 \rightarrow aCO_2 + \frac{b}{2}H_2O \qquad \textbf{4-6}$$

$$\bar{a}^{ch} = \left[\bar{g}_F + \left(a + \frac{b}{4}\right)\bar{g}_{O_2} - a\bar{g}_{CO_2} - \frac{b}{2}\bar{g}_{H_2O(g)}\right](T_0, P_0) + \bar{R}T_0 \ln\left[\frac{\left(y^e_{O_2}\right)^{a+b/4}}{\left(y^e_{CO_2}\right)^a \left(y^e_{H_2O}\right)^{b/2}}\right] \qquad \textbf{4-7}$$

Where F denotes the fuel and g is given by:

$$\bar{g}(T_0, P_0) = \bar{g}_f^\circ + \left[\bar{g}(T_0, P_0) - \bar{g}(T_{ref}, P_{ref})\right] \qquad \textbf{4-8}$$

G is the gibbs energy of the substance, and g_f^o is the gibbs energy of formation at a given T_{ref} and P_{ref}. Equation 4-7 is also applicable for hydrogen, by just removing the CO_2 components. The chemical exergy can now be determined for each component. In a mix of different components the total chemical exergy of the mix is given by equation 4-9.

$$\bar{a}^{ch} = \sum_i y_i \bar{a}_i^{ch} + \bar{R}T_0 \sum_i y_i \ln y_i \qquad \textbf{4-9}$$

For several engineering problems, a set of standard chemical availabilities has been developed. Based on a given environment the chemical exergy is calculated and presented in tables. Such tables should be used with care, and one must always be aware of the assumptions made to develop such tables.

Heating value is defined by using a combustion chamber. Inputs into the combustion chamber are fuel and air at a given temperature. They react and the heat from the reaction is extracted from the chamber until the product gas is at the same temperature as the reactants were provided. The amount of heat that is extracted form the process is termed heating value [Ertesvåg, 2000]. This could either be found via experiments, this is useful when complex mixtures react, or it could be derived from the enthalpy of formation of the substances involved.

$$h_{br} = -h^\circ_{RP} = \frac{1}{m_{br}}\left(\sum_R n_k \bar{h}^\circ_{f,k} - \sum_P n_k \bar{h}^\circ_{f,k}\right) \qquad \textbf{4-10}$$

Equation 4-10 provides the heating value for a given substance, where P and R denote the product and reactant substances respectively. N is the amount of mol of each component k. There are several types of heating values, but in most engineering appliances higher or lower heating value is used. The higher heating value is based on the utilization of evaporation heat from condensing water, thus the product contains water in liquid form. While in the lower heating value the product contains water in gaseous form.

Material Flow Analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time and it is based on the conservation of matter. It could be applied to any scale and is therefore considered a attractive method in resource management, waste management, and environmental management [Brattebø, 2006]. Equation 4-11 shows the basic concept of mass conservation.

$$\sum_{k_I} \dot{m}_{input} = \sum_{k_o} \dot{m}_{output} + \dot{m}_{storage}; \dot{m} = \frac{dm}{dt} \tag{4-11}$$

The object of MFA is to identify streams in and out of a system, as well as within the system. This could be to explore where the heavy metal in an industrial process ends up; or to trace other environmentally dangerous compounds like greenhouse gasses; or simply to produce quantitative results for use in managerial decisions. Depending on what level one wants to investigate the flows, the system should be aggregated accordingly. Figure 4-2 shows two different aggregation levels for a process. If the actions within a process is not interesting for the analysis, or the complexity is too great it is evaluated as a black box.

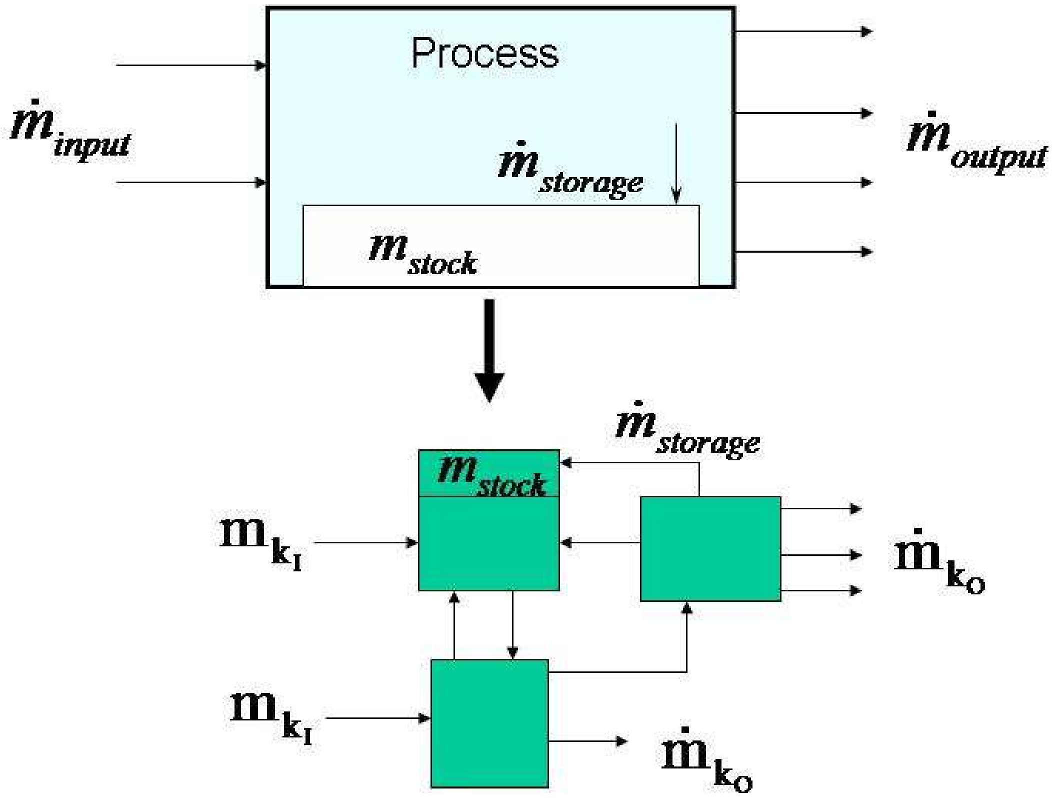


Figure 4-2: Black box aggregation

4.2 Composite Curves and the Pinch Approach Method

In industry the need of external inputs of energy is a cost related question. The use of large quantities of for instance steam represents operation costs. Industries using a lot of thermal energy, like refineries or chemical plants, would benefit from reducing their use of external heating. The composite curves are graphical tools to help setting targets for systems that consists of several streams that could be integrated in a set of heat exchanger. The curves plot temperature and enthalpy change in the streams, and gives a good picture of what qualities and quantities exists in the system. This concept is best explained using an example. Firstly we introduce the basic equations describing a pure counter current heat exchanger.

$$\Delta Q_h = mCp_h \cdot \left(T_{h,i} - T_{h,o}\right) \quad \textbf{4-12}$$

$$\Delta Q_c = mCp_c \cdot \left(T_{c,o} - T_{c,i}\right) \quad \textbf{4-13}$$

$$\Delta Q = A \cdot U \cdot \Delta T_{LMTD} \quad \textbf{4-14}$$

When analyzing a heat exchanger network we must first identify sources of heat (called hot streams) and sinks (called cold streams) from a material and energy balance [Smith, R., 2005]. This paper will explain the concept of composite curves using a simple case with two hot streams and two cold streams, given in Table 4-1.

Table 4-1: Stream Data

Stream	Ts(ºC)	Tt(ºC)	mCp (kW/ºC)
H1	200	70	50
H2	300	60	10
C1	90	180	40
C2	40	240	30

The concept is now to construct a graph for both the cold streams and the warm streams, plotted in the same temperature/enthalpy diagram. To do this the streams must divided into temperature intervals where the streams exist alone or together. In the case where two or more streams in the cold or warm category exist, the mCp values are added together, as given in equation 4-15. Table 4-2 and Table 4-3 provide data for plotting the graphs for the composite curves. In order to achieve enough driving forces in the system, a new parameter must be introduced. ΔT_{min} is the lowest difference in temperature allowable in the system. It is a complex value and is just as much an economic figure as technical. It is derived from an economical trade-of between operating costs (energy) and investment costs (heat exchangers). With all these data available the composite curves can be drawn.

$$mCp = \sum_i \left(mCp\right)_i \quad \textbf{4-15}$$

Table 4-2: Cold Stream Data

Temperature interval (ºC)	40-90	90-180	180-240
Streams	C2	C1, C2	C2
mCp (kW/ºC)	30	70	30
Enthalpy change (kW)	1500	6300	1800

Table 4-3: Hot Stream Data

Temperature interval (ºC)	60-70	70-200	200-300
Streams	H2	H1, H2	H2
mCp (kW/ºC)	10	60	10
Enthalpy change (kW)	100	7800	1000

Figure 4-3 shows the composite curves for the given stream data. From this useful information could be derived. Firstly, this graph shows the target values for a given ΔT_{min}. ΔT_{min} could either be global, providing a minimum for the whole system, or local for one or more given streams. In this example ΔT_{min} is set globally to 20°C. The target values are the minimum use of utilities if the system is fully integrated. With these streams and our given assumptions the minimum hot utility (Q_{Hmin}) is 1700 kW and the use of cooling water is (Q_{Cmin}) 1000 kW. Also, the ΔT_{min} has set what is called the "Pinch point". The pinch point is defined as the point where the two composite curves are the closest (=ΔT_{min}). In this case the pinch point is given at T_c=90ºC and T_h=110ºC. The pinch point is important because it splits the composite curves in two areas. The area above pinch in the process is balanced with the minimum hot utility. Heat is received from the hot utility and no heat is rejected; the process acts like a heat sink. Below the pinch the process acts the opposite, in balance with Q_{Cmin}. Transferring heat from above pinch is clearly possible, but heat from below pinch is not possible without violating ΔT_{min}. Although transferring from above pinch is possible, it is not useful, for any transfer of heat will cause Q_{Hmin} to rise with the same amount, thus using more utility then needed. This will conflict with the reason to make the composite curves in the first place, which is to minimize the use of utilities.

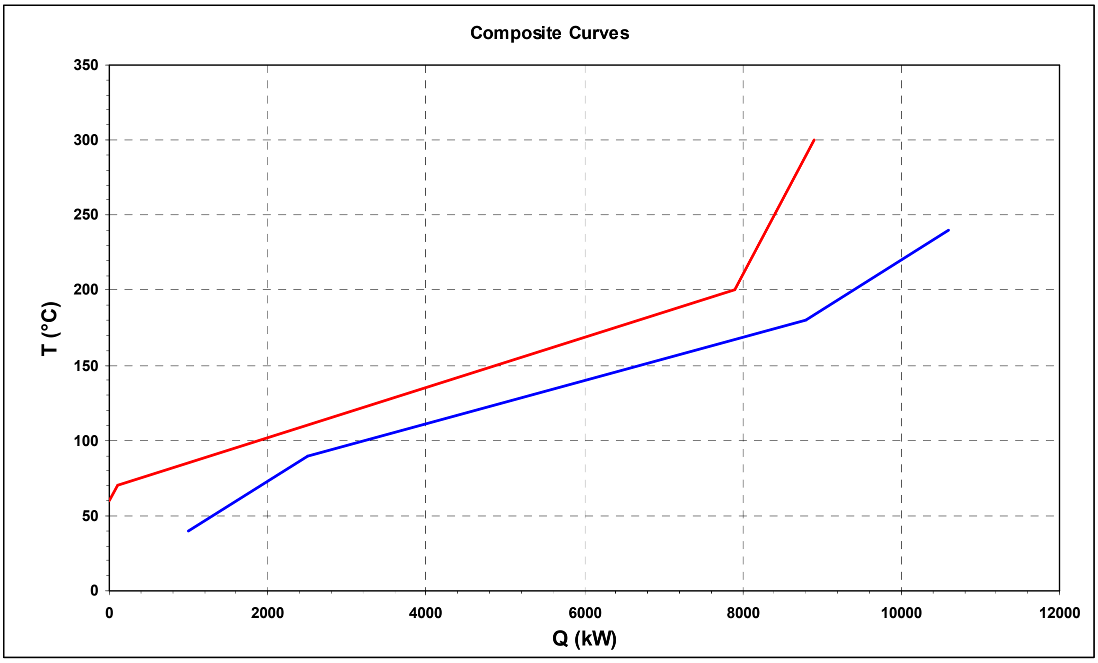


Figure 4-3: Composite Curves

The composite curves in Figure 4-3 gives the minimum use of utility. But it does not provide any information on what quality the utility must be. One of the cold streams should be warmed to 240°C, and with a given temperature difference of at least 20°C in the heat exchanger one could assume that steam at 260°C must be provided. In order to optimize the use of utilities available the grand composite curve is constructed. The x-axis shows energy and the y-axis is modified temperature T', where T' is defined by equation 4-16. The graph originates in T'_{pinch} which is 100°C on the given example. It shows that for equation 4-16 the negative sign is used above pinch (110°C-20°C/2=100°C) and the positive sign is used below pinch.

$$T' = T \pm \frac{\Delta T_{min}}{2} \tag{4-16}$$

As in the composite curves this graph must be divided into the area above and below pinch. Above pinch the curve moving away from pinch has a deficit of heat, when the curve moves towards pinch it has a surplus of heat. Below pinch the curve is the opposite and has a surplus of heat moving away its starting point pinch. The graph creates so-called pockets where the streams could exchange energy, illustrated by the grey areas of the graph. The upper blue line shows the highest quality steam needed. But steam is often available in different qualities, and the price reflects the quality. For simplicity's sake, say the given system has LP, MP and HP steam available at 160°C, 210°C and 260°C respectively. The yellow line in the graph shows the optimal use of these utilities (above pinch $T'=T-0,5\Delta T_{min}$). Of the 1700kW needed as hot utility, 500kW is provided by LP-steam, 573kW is provided by MP and thus 627kW is provided by HP.

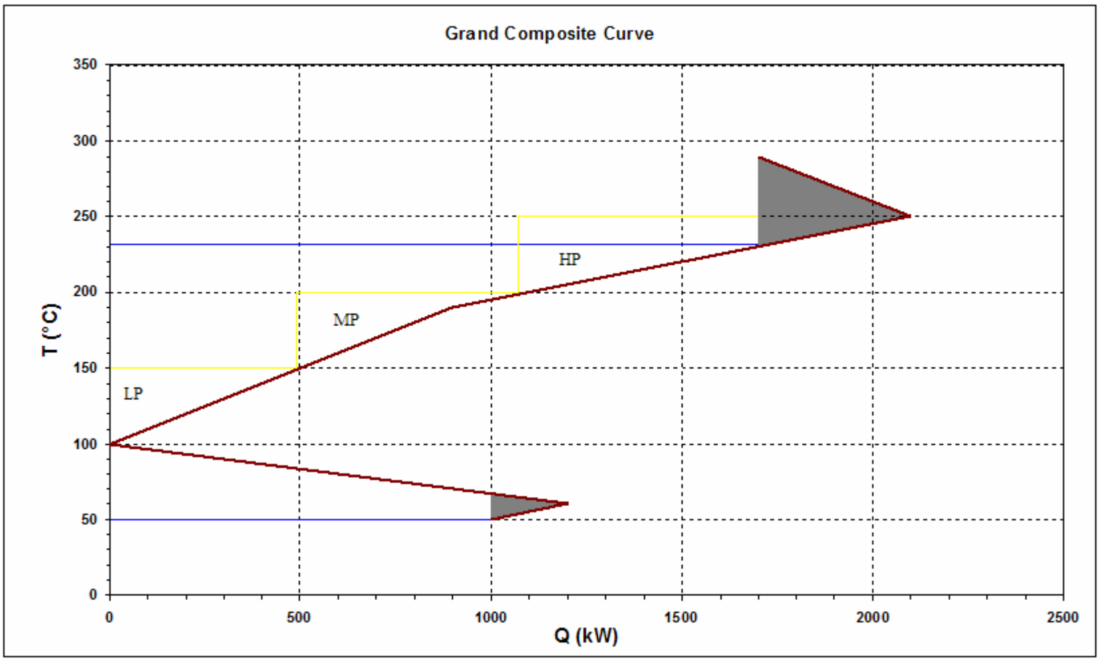


Figure 4-4: Grand Composite Curve

These graphs are often used in single plant optimization, but could also be used for other areas where energy flows occur. The important feature is the combination of quantity and quality. The amount of energy needed could be found and also the quality needed to deliver this quantity is shown in the curves. In resource optimization there is no point in using higher quality material if lower quality (and cheaper) resources are available and could deliver the same result.

5 Mosseporten – The Working Case

Methane produced in the landfill at Solgaard Landfill in Moss is currently collected and flared. The effluent is only used sporadically as heating for the land fill reception. Local investors are interested in utilizing the gas at an area close to the land fill. The area lies next to Mosseporten, the main access point into Moss. The area is currently unoccupied and the developers therefore have free hands when designing the area. Since the area is based on utilizing the landfill gas, the centre of planning is around the energy produced from this. Both electricity and heat is to be produced in a cogeneration unit. In addition to a gas powered engine, a gas boiler is installed. Heat is purposed produced at three levels; low temperature, high temperature and possibly steam. The high and low temperature heat will be used in a district heating system currently consisting of three costumers; an apartment building, a hospital and a nursing home. A heat pump is installed at the freezing hall delivering heat to the low temperature district heating. The heat pump indirectly uses part of the electricity produced in the energy central. An industrial laundry will move its facilities to the new area. In addition to producing its own steam the laundry will be coupled with the district heating systems to improve flexibility for itself and reduce oil costs. In periods of low demand in the district heating, heat of all three qualities could be delivered to the laundry.

Before entering the energy central, the gas is cleaned of components dangerous to the engine and fluids are condensed out. Figure 5-1 shows a flowchart of the connections at Mosseporten. The high temperature district heating is illustrated by red lines creating a loop, and the low temperature district heating consists of blue lines creating a loop.

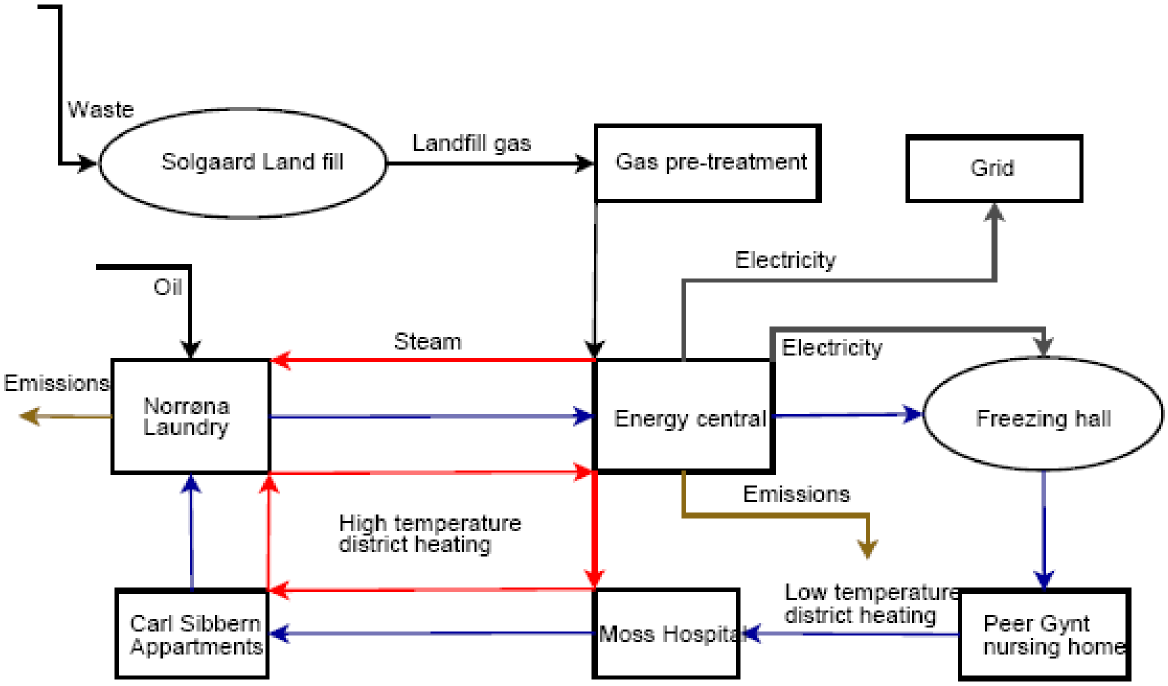


Figure 5-1: Mosseporten flowsheet

5.1 Waste and Landfilling

The whole industrial park is based in the landfill gas delivered by the landfill at Solgaard. In the conceptual framework of industrial ecology, waste is a central subject. Waste is to be reduced, and if created it should be seen as a resource. To understand the process around waste, and land filling especially, a short presentation of a complex problem is given in the following chapters.

Waste has several environmental impacts. The creation of waste is obviously an area problem, and the release of gasses contributing to global warming is also a factor to be assessed. The main problem is though often connected to substances in the waste that are toxic or otherwise harmful for humans or the environment. Waste management is a complex problem which includes several different tiers. Figure 5-2 shows an illustration of the possible processes involved in solid waste treatment.

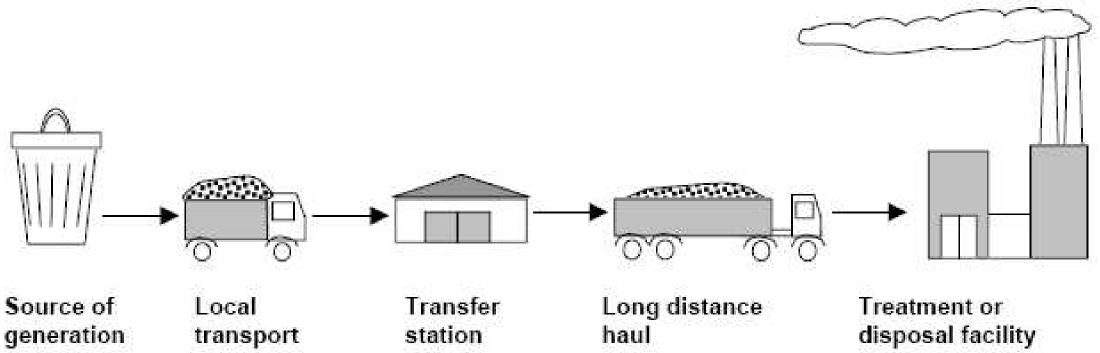


Figure 5-2: Schematic illustration of waste management [Poulsen, 2003]

Waste is basically the product of society's use of natural resources. Depending on how this system is managed, these resources end up either as disposable waste or looped within the system in terms of recycling. There are several ways of disposing the waste and treatment differs widely from country to country. Also within each country the treatment methods have changed in the last 20-30 years. The use of material recycling and energy creation has increased, while older, more area and environmental intensive, solutions like land filling has decreased. Figure 5-3 shows the distribution for waste treatment in Norway in 2005. Norway has low percentage of land filled waste compared to other European countries [Miljøstatus, 2006].

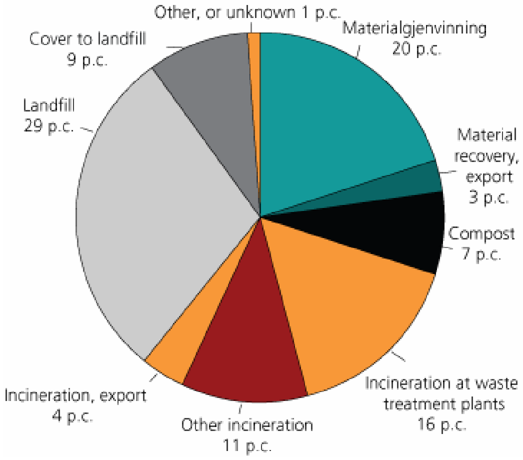


Figure 5-3: Waste treatment in Norway 2005 [SSB, 2006]

The amount of waste produced in a country is connected to the nation's consumption of goods. Nations with high GDP tend to produce larger amounts of waste. The exception to the rule is Cyprus which produces the second highest amount of waste per capita in Europe [Miljøstatus, 2006] despite only having Europe's 18th highest GDP per capita [World Bank, 2004]. The Norwegian authorities have set a norm that the development of waste production should not surpass the development in GDP. In the period 1995-2005 household waste per capita in Norway has increased from 269 kg to 407 kg. The total amount of waste produced in Norway has risen from 7,4 tons in 1995 to 9,7 tons in 2005; an increase of 33 per cent. In the same period the GDP has increased by 31 per cent [SSB, 2006]. This is mainly due to the large increase in industrial waste from 2003 as seen in Figure 5-4.

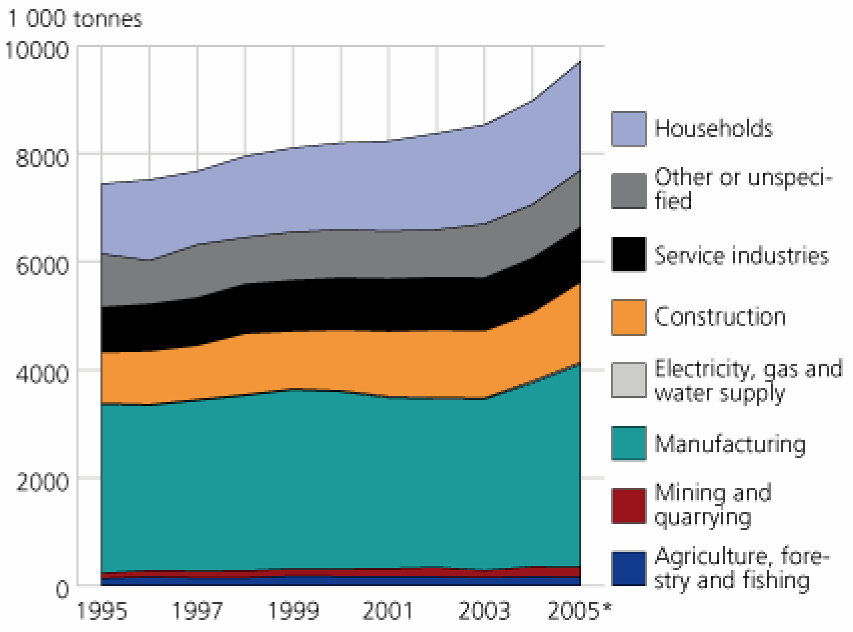


Figure 5-4: Waste in Norway by source [SSB, 2006]

5.1.1 Landfills

Landfills are considered the least environmentally friendly method of disposing waste. Table 5-1 shows some potential environmental impacts from landfills. Therefore, in the latest years, alternative disposal processes have been used more and more. In Norway, there has been a decline of 13 per cent in waste sent to landfills [SSB, 2006].

Table 5-1: Potential environmental impacts of landfills [Poulsen, 2003]

Air	Soil	Water
• Global warming • Ozone depletion • Toxic gases • Odour • Noise	• Birds, rodents, insects • Fly waste, dust • Explosion and fire hazard • Vegetable damage • Soil pollution	• Surface water pollution • Ground water pollution

5.1.1.1 Landfill construction

To minimize the environmental effects, it is important that the landfill is properly constructed and maintained. The most important elements of a modern landfill facility are bottom membrane, percolate collection system, gas collection system, percolate irrigation system and top cover. Figure 5-5 shows the different elements of a modern landfill.

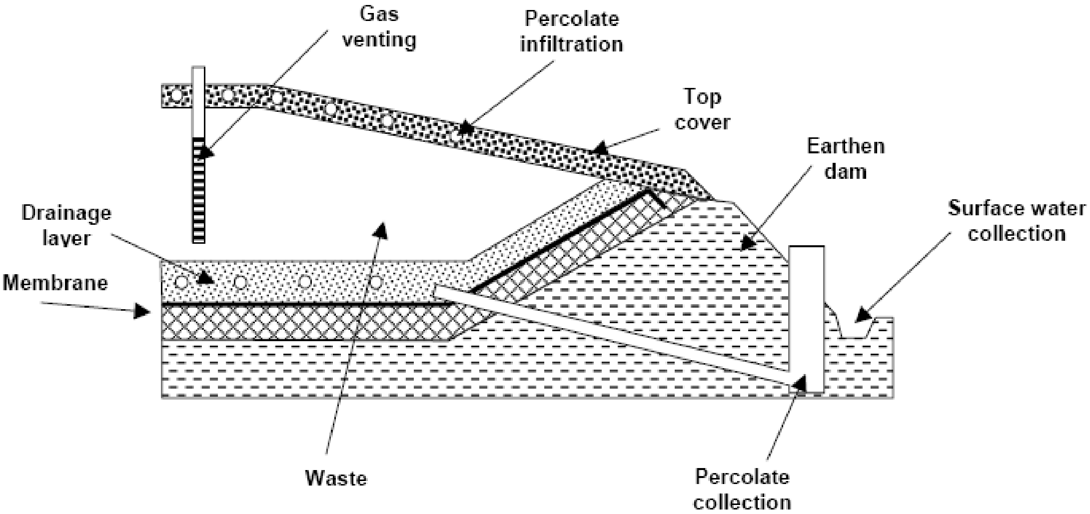


Figure 5-5: Structural elements of a modern land filling facility [Poulsen, 2003]

The purpose of the bottom membrane is to reduce the leaching of contaminants out of the landfill. It is not practically and economically possible to ensure that the membrane is 100% effective and the quality is determined by weighing production costs against possible environmental problems. It is extremely important that the construction of the membrane fulfils the quality standards set for landfills. Mistakes and errors are hard or impossible to fix afterwards. Above the membrane is the drainage system and its purpose is to ensure an effective collection of percolate during the deposition and the active phases and minimize the risk of uncontrolled leaching from the landfill. The gas venting system is placed trough the waste, and will be further described in chapter 5.2.1. The percolate collected at the bottom of the landfill can be either directly sent to a wastewater treatment plant or it can be recycled to the top of the landfill. The construction and design of the top cover is done based on the availability of construction materials in the surrounding area as well as on the functional demands to the cover. The purpose of the plant cover is protection against erosion and dust emissions and it enhances vapour transported from the growth layer, reducing percolate formation. It could be constructed as permeable or non-permeable depending on type of landfill being closed and later areas of use [Poulsen, 2003].

5.1.1.2 Land filling in Norway

Land filling has decreased in Norway the last years, but seems now to have been stabilized at its current level. Current regulations concerning landfills states that all land fills must have double layer of ground sealing and a system to gather and clean the leachate. All land fills not built according to the new regulations have been evaluated for environmental consequences. Those land fills without proper treatment of leachate has been shut down, while the rest have received demands to emission-levels and will be subsequent to surveillance. By 2009 all land fills must be up to regulation [Miljøstatus, 2005]. Of the about 2,4 Mtons of waste land filled in Norway most of it is either considered hazardous or unspecified. Figure 5-6 shows the distribution of waste land filled in Norway in 2004.

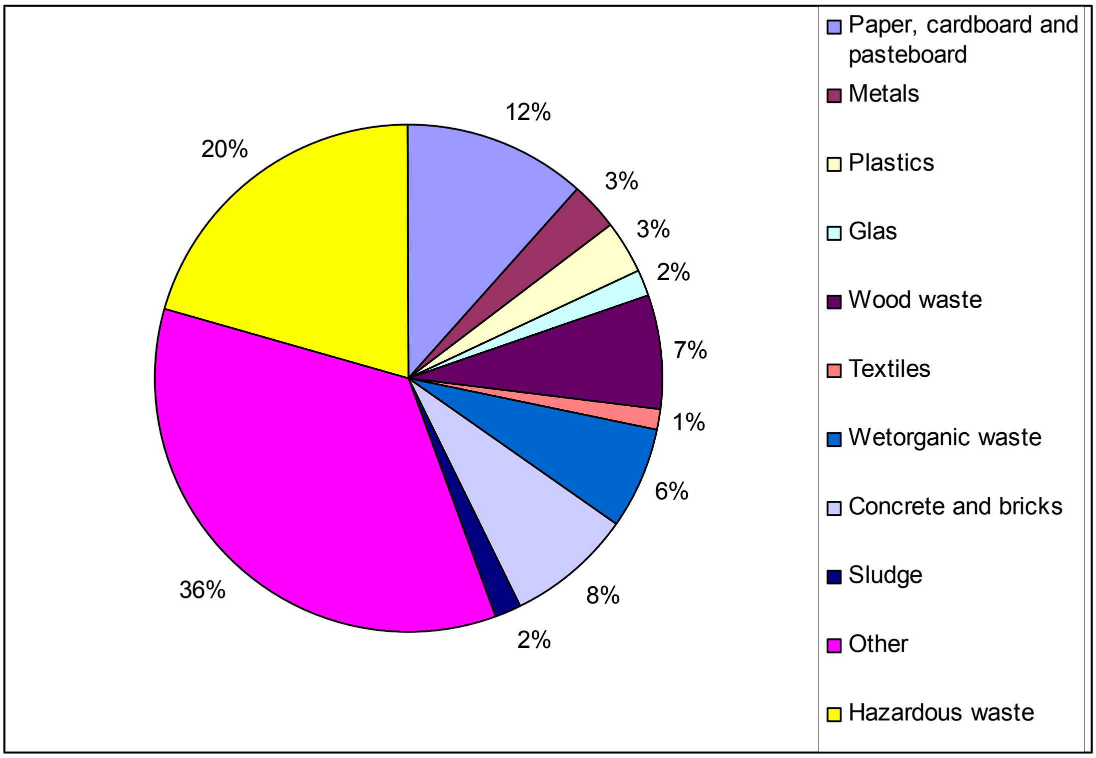


Figure 5-6: Distribution of waste land filled in Norway 2004

5.2 Landfill Gas

In 2005 more then 26 per cent of Norway's methane emissions originate from landfills [Miljøstatus, 2007]. Methane is produced by waste in a chemical process known as waste decomposition or degradation. The process is complex, and is influenced by several factors, such as temperature, moisture content, composition of the waste and the diversity of substrates for microbial degradation. Several models have been suggested to divide the process into different stages, most commonly used models usually consists of three or five stages. Bove and Lunghi [2006] present a five stage model to understand the process. Figure 5-7 shows the development through these five stages.

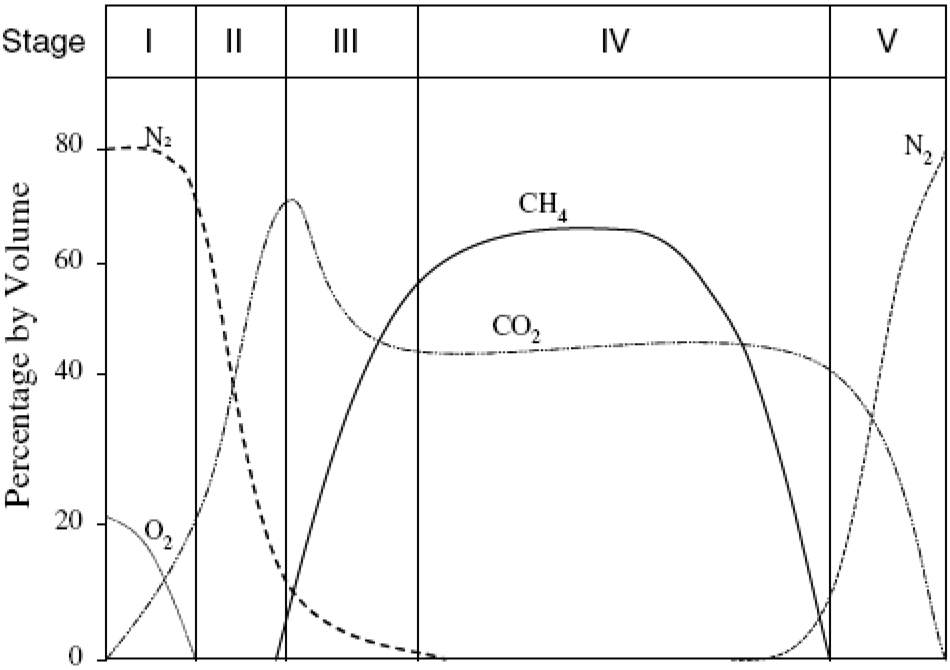


Figure 5-7: Landfill gas composition during the five stages [Bove and Lunghi., 2006]

I. Aerobic decomposition. In this phase, wastes are digested by bacteria, in the presence of air. Heat is produced, while O2 is consumed for CO2 production. The time frame, depending on specific conditions, ranges from months to one year.
II. Acidogenic. In this phase, anaerobic conditions are established. As a result, H2, CO2, H2O and organic acids are produced. Because of the anaerobic conditions, the energy release rate is low. Because of acid formation, the leachate pH can drop below 5.
III. Acetogenesis. In this phase, the oxidation of acids and alcohols to acetic acids plus CO2 and H2 takes place. The chemical oxygen demand (COD) noticeably increases due to the dissolution of acids and the leachate.
IV. Methanogenesis. Products of acetogensis are converted to methane and CO2, and H2 is consumed. The methane content depends on the available substrates.
V. Maturation. Because of substrate depletion, gas production drops-off. [Bove and Lunghi, 2006]

Experiences from United Kingdom suggest that methane typically begins to be produced two years after waste deposition, peaking after about five years with a following slow declination [Brown and Maunder, 1994]. As Figure 5-7 shows, other compounds are also produced, mainly CO2. CO2, in addition to being a green house gas, could also limit the area of use for the methane. For example, gas turbines need higher concentration of methane to function properly. LFG also contains a small amount of sulphide, often in the form of hydrogen sulphide. Hydrogen sulphide is toxic and highly corrosive, being a risk for both humans and pipelines and machinery. An American study [Aucott, 2006] showed that heavy metals, often a problem concerning leachate, are rarely emitted with the gas. Only very small amounts of mercury were found.

From 2009 land filling of biodegradable waste will be illegal in Norway, in addition to the already active prohibition of land filling of organic waste. In the spring of 2002 the Norwegian Ministry of the Environment passed a new regulation considering deposition of waste. It was an implementation of the European Union's new directives. Among the areas it constitutes is the treatment of methane produced in landfills. Appendix 1, section 4 of chapter 9 of the new law for waste management states:

"4. Gas control
4.1. Measurements to control accumulation and leakage of landfill gas should be taken.
4.2. Landfill gas shall be collected at all landfills which receive biological degradable waste, and the gas must be treated. If the gas is not used to produce energy, it must be flared. Collection, treatment and utilization of landfill gas must be executed in a way that does not involve dangers for health or the environment." [Lovdata, 2004, my translation].

Landfill gas could be utilized in different ways. Fired directly into a boiler or furnace, or used to produced electricity; or a combination of this. The gas could also be chemically treated to produce bio-diesel, methanol etc. If suitable and the infrastructure exists the gas could be cleaned and added to the national pipeline system. In Norway the utilization of landfill gas is expanding, although the most common fate of landfill gas today is flaring. Figure 5-8 shows the development of methane tapping in Norway since 1988.

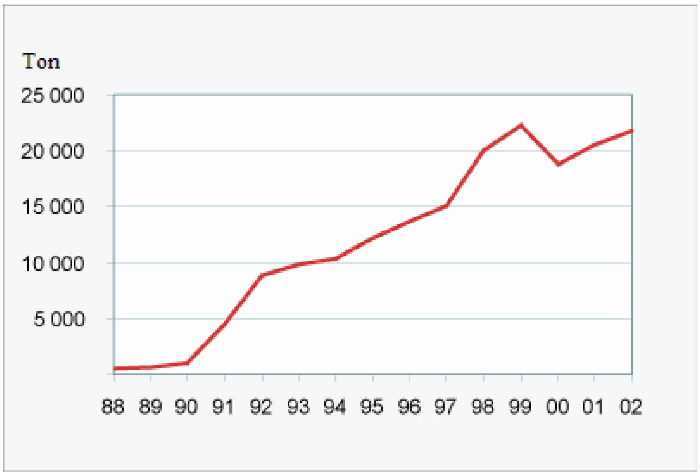


Figure 5-8: Reported methane tapping form land fills in Norway 1988-2002 [Miljøstatus, 2005]

5.2.1 Collecting the gas

As a consequence of the new law passed in 2004 all landfills in Norway that could receive organic waste were obliged to install a way to collect the gas. There are two ways of collecting the gas, either passive or active. The most efficient and commonly used is the active type. Instead of just perforated tubes placed through the waste, the active collection uses vacuums or pumps to provide a preferred route for the gas. A system of valves and regulators controls the suction on each pipeline. Figure 5-9 shows an illustration of a collection system, complete with waste water treatment, storage and electricity production.

Figure 5-9: Illustration of LFG-collection and utilization

5.2.2 Producing Landfill Gas

Since landfill gas is naturally occurring process, there are several factors that are not controlled. And since the amount of gas and the percentage of methane produced vary with several factors one would want to make the process more industrial. Also, the composition of the waste is important for the process. Equation 5-1 shows Buswell's formula for basic stoichiometric calculations of methane production. And from Buswell's the theoretical maximum amount of methane produced, given the composition of the waste, could be derived as in equation 5-2.

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3 \qquad \textbf{5-1}$$

$$B_{th} = 22400 \frac{\left(\frac{4a+b-2c-3d}{8}\right)}{12a+b+16c+14d} \left[{Nm^3 CH_4} \big/ {tonVS} \right] \qquad \text{5-2}$$

In the last 10-15 years three basic principles of landfill gas (or biogas, as the gas no longer is produced in landfills) production has developed. The process is either dry (>25% dry solids), wet (<15% dry solids) or half-dry, and the European marked consists of about the same amount of dry processes as wet processes, with only a small amount of half-dry processes [Nedland and Paulsrud, 2004]. Within the different processes there are several different design and engineering solutions, depending on the kind of waste used, size of the plant, location and constructor. Different processes aside, the main problem for every installation is to gain a continuous production. It usually takes a year from starting production until it stabilizes. In Norway, the process of building biogas plants based on organic waste has been slow and neighbour countries as Sweden and Denmark have more and longer running plants.

In 1999 the Ministries of the Environment and Agriculture created a program called ORIO. And in 2004 they delivered a report; Experiences with biogas plants for treatment of organic waste [Nedland and Paulsrud, 2004]. Experience from the only Norwegian plant with good data investigated in the report, the Mjøs-plant at Lillehammer, is shortly presented in the following chapter.

5.2.2.1 The Mjøs-plant at Lillehammer

The plant is planned to receive food waste from 185.000 residents in the area, and designed for 14.000 tons of waste each year. Because the waste is collected by three different companies there is some variation in the state the waste is delivered and what is in the sorted parcels. The plant is based on a special process called thermal hydrolysis and produces compost as well as biogas. Thermal hydrolysis means splitting cells and long chain molecules by application of water and heat in a pressurized environment. Figure 5-10 shows a simplified flow sheet of the plant.

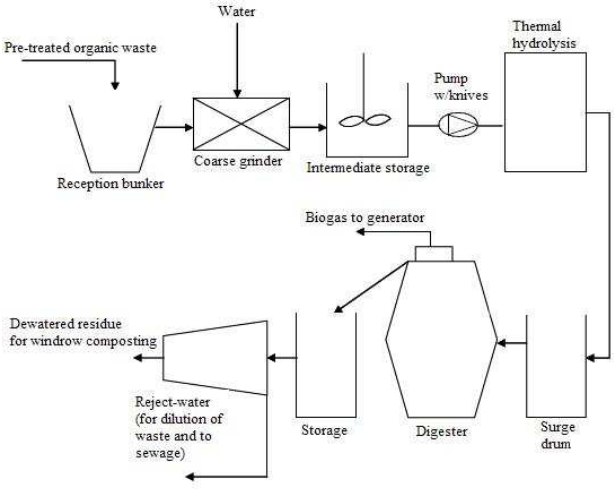


Figure 5-10: Flow sheet of the Mjøs-plant

Measurements from the plant show good reduction in the digester; even though the plant was not at full load and that the retention time was high (27 days). The amount of gas produced was also high, providing 0,67 $Nm^3/kg\ VS_{added}$ and 1,07 $Nm^3/kg\ VS_{reduced}$. The latter is close the its assumed theoretical value of 1,1 $Nm^3/kg\ VS_{reduced}$, based on a methane content of seventy per cent [Paulsrud and Storhaug, 2003]. The methane percentage recorded is 61-62 per cent, this is in compliance with other studies done on biogas plants in Denmark [Christensen, Lund Hansen, Kirkeby, la Cour Jansen, Svärd, Kjems Toudal, Rasmussen, Hulgaard, Gruvberger, 2003]. In addition to the gas, a certain amount of compost is produced.

The operation experiences from the Mjøs-plant shows that weaknesses in the pre-treatment of the organic waste have created the largest problems in regards to running the plant. The incoming waste is now put firstly put through a drum sieve with knives installed. It cuts open plastic bags and sorts out unwanted elements of plastic, paper and textiles. Nedland and Paulsrud's [2004] report states that any future biogas plant in Norway must have this (or similar) pre-treatment. Several other cleaning and separating processes have been implemented to remove unwanted compounds in the process.

5.2.3 Landfill Gas at Mosseporten

As a part of the development of the Mosseporten area a study was undertaken to investigate the amount and quality of the landfill gas. The study was conducted using a model used by the Norwegian Pollution Control Authority (SFT) for calculating methane emissions from landfills. There has however been a discussion on how accurate this model is. In 2005 SFT changed their models, and the new calculations showed emissions almost half of the old calculations [SFT, 2005]. There is therefore some uncertainty regarding the prognosis of future gas production shown in Figure 5-11. As the figure shows, the production will rise till about 2011/2012 where the production will be about double of what it is today. It is assumed that all the organic compounds are anaerobely degraded. And it must be noted that the model has no corrections in respect to temperature and rainfall, both which are important to the decomposition [Svensen, 2006].

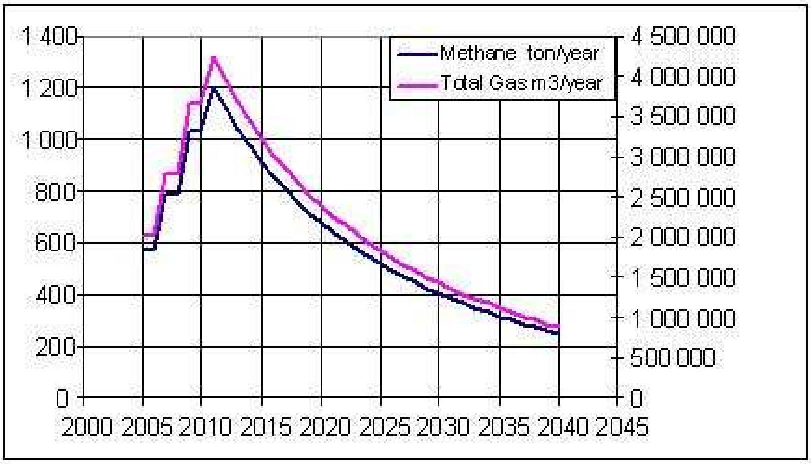


Figure 5-11: Production of landfill gas at Solgaard [Svendsen, 2006]

Measurements of the composition of the landfill gas have been conducted for the month of September 2006. There is a lot of uncertainty connected with these measurements. All the measurements are shown in Appendix A – Gas Measurements

Appendix A – Gas Measurements, while the average results are presented in Table 5-2. As the reader would notice the sum of the components does not add up to a hundred per cent. This shows the large uncertainties in the measurements. For the calculations conducted in this paper it is assumed a gas flow of 236m^3/h with 40 per cent methane and 60 per cent CO_2.

Table 5-2: Average measurments

Substance	CH4	H2S	CO2	O2
Average value	41,75 %	395,5 ppm	33,63 %	1,19 %

5.3 Energy Demand at Mosseporten

Assessments of power and energy in the district heating have been made based on historical data and assessment tools for similar buildings. In the low temperature network the peak power is about 1900kW with a total annual energy use of 2,44 GWh. The gas engine intercooler and the heat pump could deliver 770kW of power throughout the year covering 2,2 GWh of the energy demand. The duration curve for the low temperature district heating is shown in Figure 5-12.

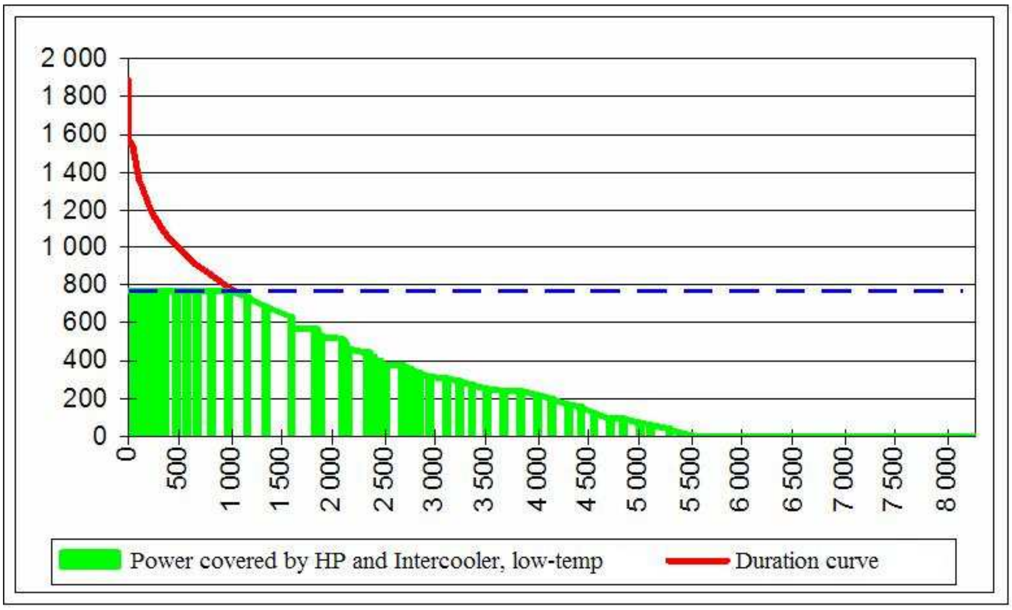


Figure 5-12: Duration curve low temperature

In the high temperature network the peak power is about 1800 kW with a total energy use of 3,5 GWh. The gas engine and gas boiler provides 530 kW of power annually covering 2,5 GWh of the energy demand. The duration curve for the high temperature district heating is shown in Figure 5-13.

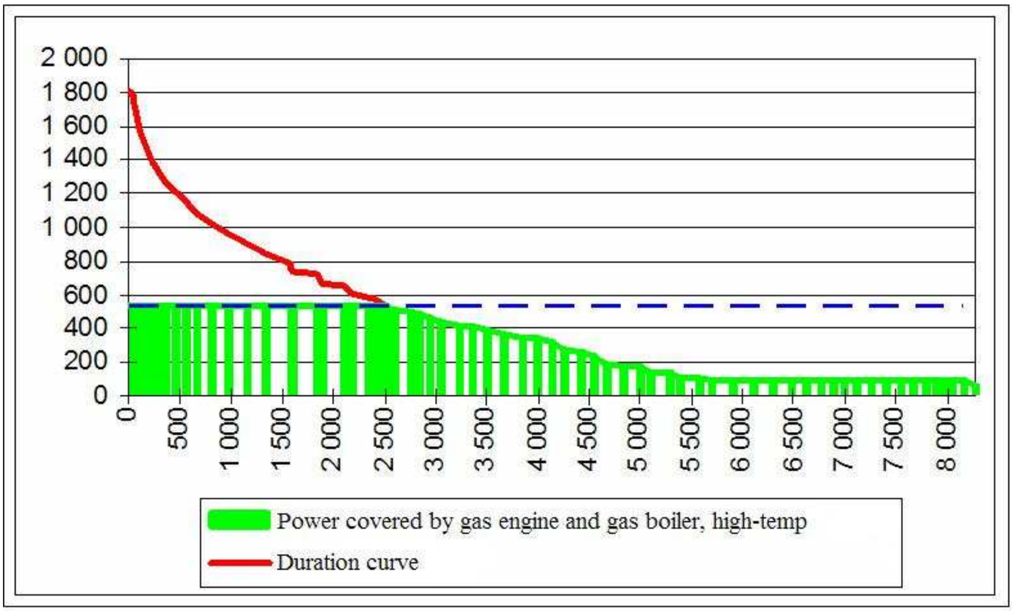


Figure 5-13: Duration curve high temperature

The curves show that the peak power, both in the high and low temperature systems is higher then could be delivered by the daily running of the system. To solve this problem an oil-fired boiler is installed.

A more stable user of energy, not included in the district heating duration curves is the laundry. Currently installed are two oil boilers of 2 and 1 MW, delivering saturated steam at 180°C. Previously the laundry was using the 2 MW at full load. However, instalment of two new dryers has lowered their use of steam. An energy study of the laundry conducted in January showed that the use of steam has been lowered with about 500 kW by substituting the dryers [Hjelm, 2007]. Thus, the laundry is in need of about 1500kW of steam.

5.4 Developing the Industrial Park

In the development of the industrial park at Moss, the developers have had the concept of industrial ecology in mind. The energy source is fuelled by a renewable energy source, and some of the citizens are provided heat from the waste they have thrown away. It also seeks to utilize every possible energy-source and -sink for maximum use of heat energy. There has also been a good dialogue between the providers of the landfill gas (MOVAR), the investors, designers, engineers and tenants of the lot. It is therefore a good start for developing an EIP. The goal of this paper has been to introduce new processes in the system to which exploits the resources available. In the development the focus has been on reducing the emissions of greenhouse gasses and energy efficient utilization of heat. It has also been focused on the possible use of end products locally. This chapter will chronically present how the processes have been developed. This because the chain-of-thought used to develop this park could show how such parks could be developed. It also shows why some preferences have been chosen in the simulations described later in the paper.

The first step in developing the park was thinking how the LFG could be better utilized. The gas contains large quantities of CO_2, and the amount fluctuates to some degree which could cause the proposed gas engine to stop working. CO_2's boiling point is relatively sensitive to pressure increases, and given that the park was to include a freezing hall a relative small extra investment would have to be made to condensate the CO_2. There were two reasons for this. Firstly, a cleaning process with a buffer tank with natural gas would deliver a constant flow of pure methane to the engine, resulting in a safer running. Secondly, the CO_2 could be used as a resource instead of being emitted to the atmosphere, contributing to global warming. The county of Østfold has two large industries; agriculture and chemical processing. Two processes fit this area well; a green house and urea-production. The greenhouse could also benefit from sources of low temperature heat available in the system. Urea is crated from carbon dioxide and ammonia and therefore an ammonia plant could therefore fit the park. Ammonia is produced by nitrogen and hydrogen, both which require large amounts of energy and high temperatures. Hydrogen is produced by reforming natural gas and steam. In addition to hydrogen, the reforming process also produces CO, CO_2 and steam, thus providing another source for CO_2 for the urea process. The CO and hydrogen remaining could be burned to aid the reforming process. The nitrogen is produced by extracting nitrogen from the air, leaving almost pure oxygen. This led again to the thought of burning the cleaned LFG with pure oxygen, making it easy to clean the flue gas. This led to five distinct new processes introduced into the system; a greenhouse with added carbon dioxide, a urea-plant, an ammonia plant, steam reforming and CHP with CO_2-capture. The system is shown in Figure 5-14.

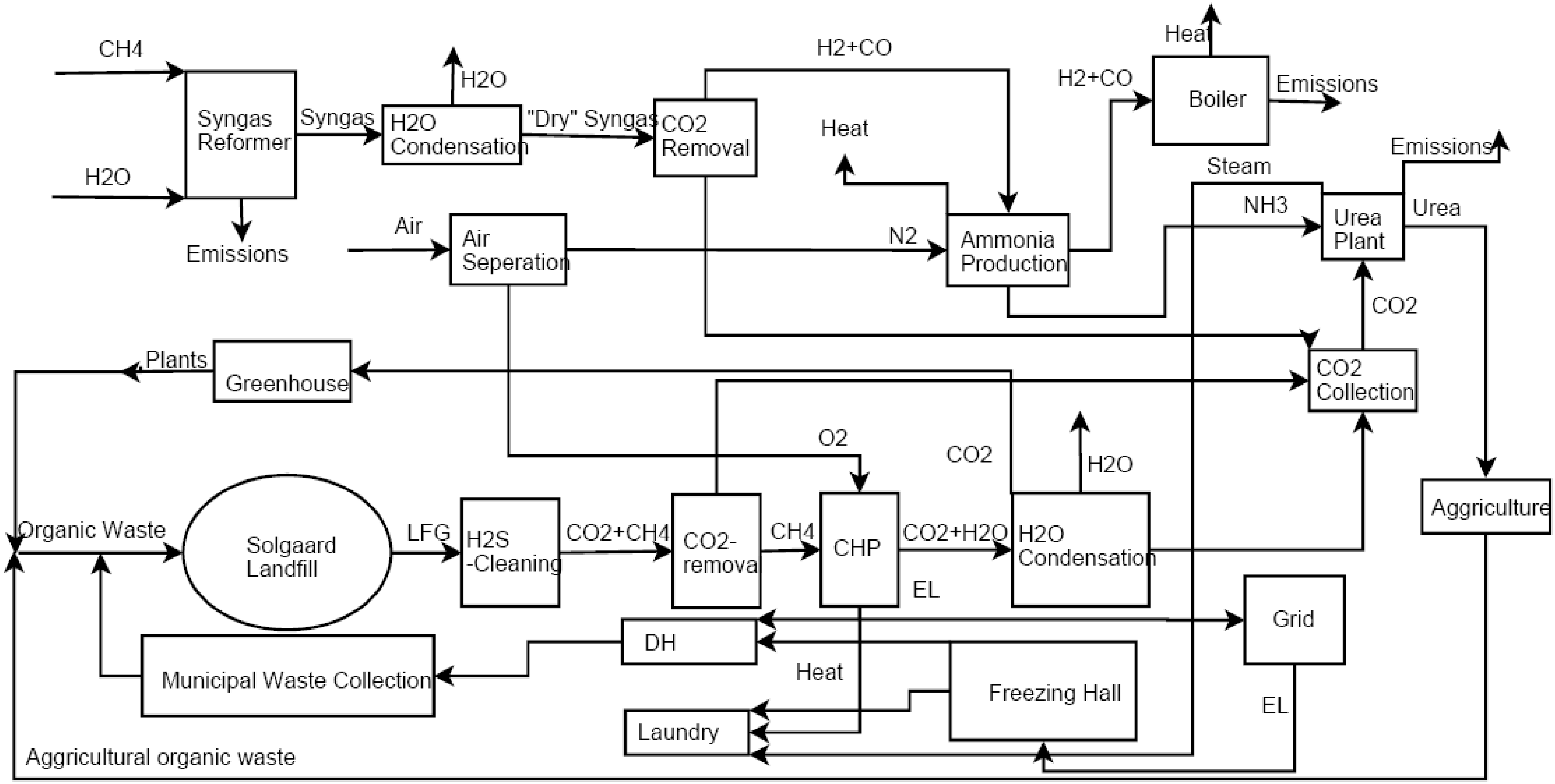


Figure 5-14: System flowsheet of the EIP

5.4.1 Greenhouse with Added Carbon Dioxide

All the food we eat and all the fossil fuel we use is a product of photosynthesis, a process that coverts energy in sunlight to chemical energy to be used in biological systems. CO_2 is converted to carbohydrates in a complex set of reactions. Although the process is complex, the photosynthesis is often presented as shown in equation 5-3. It shows that in addition to nutrients, water and solar energy, carbon dioxide is a deciding factor in the growth of plant.

$$6CO_{2(gas)} + 6H_2O_{(liquid)} + solar\_energy \rightarrow C_6H_{12}O_{6(aqueous)} + 6O_{2(gas)} \qquad \textbf{5-3}$$

The amount of overall CO_2 fixation in plants growing under optimal conditions is limited primarily by the amount of CO_2 available. Therefore, the increase of CO_2 in the atmosphere will lead to somewhat higher rates of plant growth in environments where the CO_2 concentration limits growth rates. This is usually the case in an agricultural setting, where nutrients and water availability are not limiting. However, also in natural conditions, where limitations other than the CO_2 concentration will generally limit plant productivity, plant productivity has been found to often increase upon increasing the CO_2 concentration [Vermaas, 1998]. Figure 5-15 show the effect of added carbon dioxide on the photosynthesis.

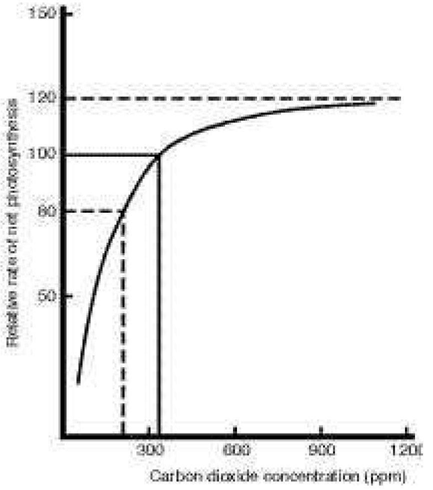


Figure 5-15: The effect of carbon dioxide on net photosynthesis [MAFRA, 2003]

Normally the level of CO_2 in outside air is about 340 ppm by volume. All plants grow well at this level, but as CO_2 levels are raised, photosynthesis increases, resulting in more sugars and carbohydrates available for plant growth. The decrease in photosynthesis when CO_2 level drops from 340 ppm to 200 ppm is similar to the increase when the CO_2 levels are raised from 340 to about 1300 ppm as seen in Figure 5-15. As a rule of thumb, a drop in carbon dioxide levels below ambient has a stronger effect than supplementation above ambient [MAFRA, 2003]. There are two factors reducing the carbon dioxide levels in greenhouses; photosynthesis and natural air exchange. The natural air exchange is dependent on several factors such as gutter height and width, glazing and type of ventilation (forced or natural). The air exchange and photosynthesis combined a flow of 0,5-0,6 kg of CO_2/hr/100 m^2 must be added in a “standard” greenhouse to maintain a CO_2 level of 1300 ppm [MAFRA, 2003].

5.4.2 Steam Reforming

Steam reforming is widely used in industry today. In the presence of a catalyst (usually nickel) and at high temperatures hydrocarbons are converted in what is called oxygenolysis reactions. Equation 5-4 shows this for methane and 5-5 gives the reaction for any other hydrocarbon.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \left[\Delta\mathrm{H} = 206\mathrm{kJmol}^{-1}\right] \tag{5-4}$$

$$C_nH_m + nH_2O \rightarrow nCO + \left(\frac{m}{2} + n\right)H_2 \tag{5-5}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \left[\Delta\mathrm{H} = -41\mathrm{kJmol}^{-1}\right] \tag{5-6}$$

Equation 5-6 is the associated water-gas shift reaction, and over an active catalyst it almost always occurs in the same reforming process as 5-4. They are both reversible and often reach equilibrium at high rates of reaction. As the ΔH indicates, equation 5-4 is an endothermic reaction. Thus the reforming requires heat to provide wanted results. The composition of the product is governed by the reactor temperature, operating pressure, feed compositions and the amount of steam in the feed stream. The steam reforming is applicable for hydrocarbons not heavier then naphtha. For heavier hydrocarbons a method called partial oxidation, not presented in this paper, is used [Yürüm, 1995].

5.4.3 Urea Production

Urea has grown to be the market leader in nitrogen providing fertilizer. It now constitutes almost half of the worlds 37,6 mill tonnes (1998) of nitrogen fertilizer consumption [IFA, 2002]. It is the fertilizer which provides the largest amount of nitrogen per mol. The commercial synthesis of urea involves the combination of ammonia and carbon dioxide at high pressure to form ammonium carbamate which is subsequently dehydrated by the application of heat to form urea and water.

$$\mathrm{2NH_3 + CO_2 \leftrightarrow NH_2COONH_4 \leftrightarrow CO(NH_2)_2 + H_2O} \tag{5-7}$$

Equation 5-7 shows simplified steps for producing urea. The process is really more complex in its development. This is especially because of the different properties of the two reactions. The first reaction producing ammonium carbamate is exothermic and is completed under high pressure. The second reaction is endothermic and much slower, being the limiting factor for converting ammonia and carbon dioxide. Conversion of carbon dioxide is in the order of 50-80 per cent, increasing with temperature and ammonia/carbon dioxide ratio. The design of commercial processes has involved consideration of how to separate the urea from the other constituents, how to recover excess ammonia, and decompose the carbamate for recycle. Attention was also devoted to developing materials to withstand the corrosive carbamate solution, which is a salt, and to optimise the heat and energy balances. Today, mainly four processes are used in urea production.

- Carbon dioxide stripping process. Ammonia and carbon dioxide are converted to urea via ammonium carbamate at a pressure of approximately 140bar and a temperature of 180-185°C. The molar NH3 /CO2 ratio applied in the reactor is 2.95. This results in a carbon dioxide conversion of about 60 per cent and an ammonia conversion of 41 per cent. The reactor effluent, containing unconverted ammonia and carbon dioxide is subjected to a stripping, using CO2 as stripping agent. A 99.7 per cent urea melt is produced
- Ammonia stripping process. Ammonia and carbon dioxide are converted to urea via ammonium carbamate at a pressure of 150bar and a temperature of 180°C. A molar ratio of 3.5 is used in the reactor giving a carbon dioxide conversion of 65 per cent. The reactor effluent enters the stripper where a large part of the unconverted carbamate is decomposed by the stripping action of the excess ammonia.
- Advanced cost and energy savings (ACES) process. In this process the synthesis section operates at 175bar with an NH3 /CO2 molar ratio of 4 and a temperature of 185 to 190°C. The reactor effluent is stripped at essentially reactor pressure using CO2 as the stripping agent. The aqueous urea solution is first concentrated to 88.7 weight per cent in a vacuum concentrator and then to the required concentration for prilling or granulating.
- Isobaric double recycle (IDR) process. In this process the urea synthesis takes place at 180-200bar and 185-190°C. The NH3 /CO2 ratio is approximately 3.5-4, giving about 70 per cent CO2 conversion per pass [EFMA, 1997].

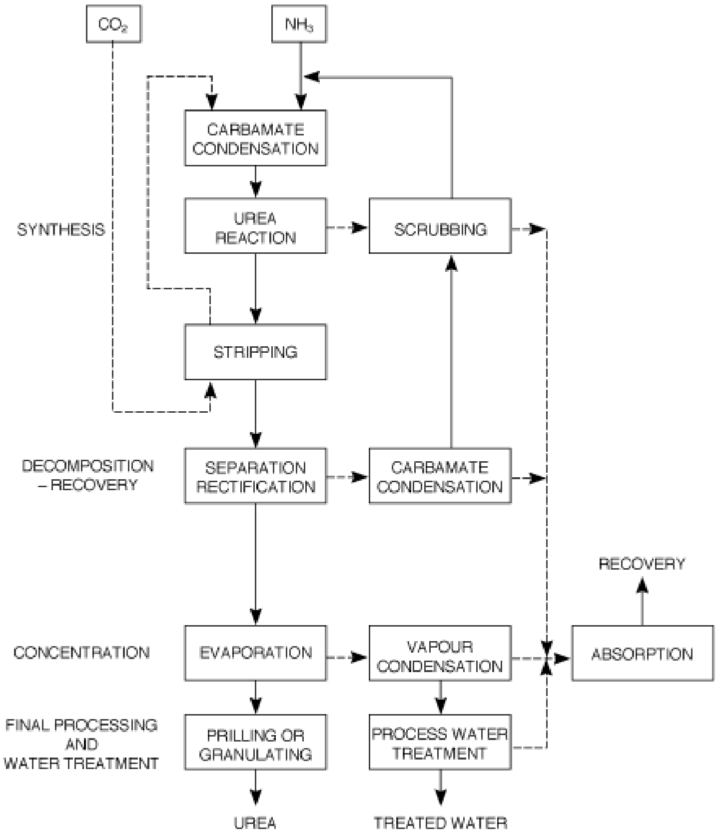


Figure 5-16: Block diagram of a total recycle CO_2 stripping urea process [EFMA, 1997]

5.4.4 Ammonia Production

Ammonia is used several places in society, either as a component in chemical processes or in its pure form as a cooling agent. Ammonia is the result of a reaction between nitrogen and hydrogen, often referred as the Haber-Process after the German chemist Fritz Haber [AUS-e-TUTE, 2007]. The reaction is exothermic, as shown in equation 5-8.

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g) \qquad \left[\Delta H = -46 \mathrm{kJmol}^{-1} NH_3\right] \qquad \mathbf{5\text{-}8}$$

The reaction operates best with medium high temperatures, very high pressure and a catalyst (usually porous iron, Fe_3O_4). The optimal process is found by considering two chemical principals, namely the equilibrium constant and Le Chetalier's Principle (LCP). LCP tells us that increasing the pressure will shift the equilibrium towards the right. System will adjust to reduce the effects of change, thus it will reduce the pressure by having fewer molecules. The same effect will make the equilibrium shift towards the left with increased temperature, due to the reaction being exothermic. Thus, high pressure and low temperature should be good. But because of the high equilibrium constant at low temperatures, the reaction is extremely slow at low temperatures. Figure 5-17 shows the yield as a function of pressure for different temperatures.

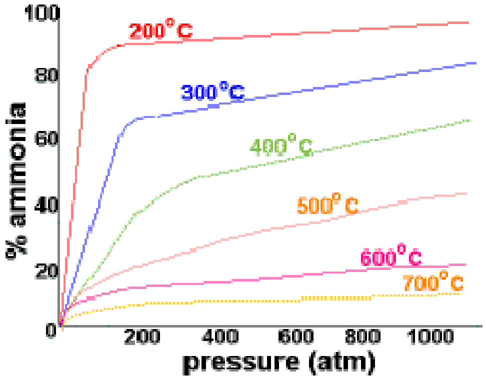


Figure 5-17: Ammonia yield as a function of temperature and pressure [AUS-e-TUTE, 2007]

As a compromise the synthesis of ammonia takes place on an iron catalyst at pressures usually in the range 100-250bar and temperatures in the range 350-550°C. Only 20-30 per cent is reacted per pass, so recycling of nitrogen and hydrogen gasses is used, resulting in a 97 per cent conversion of the reactants. This could in turn be condensed to deliver almost pure ammonia [EFMA, 1995].

5.4.5 Production of Nitrogen

Nitrogen, one of the largest volume industrial gases, is produced commercially as a gas or as a liquid by several methods. Most common are:

- Cryogenic Air separation, a process in which air is compressed and cooled to cryogenic temperatures, liquefied and then, relying on different boiling points, separated into its components in a distillation column. This can be done in a co-products plant producing nitrogen, oxygen and argon, or in a Nitrogen Plant (N-Plant) which produces high purity nitrogen only.
- Membrane separation, a non-cryogenic technology that uses hollow-fibre polymer membranes to separate gaseous nitrogen from air by selective permeability. Membrane nitrogen is usually lower cost than cryogenically produced nitrogen, but also delivers lower purity.

Cryogenic distillation accounts for approximately 85 percent of nitrogen production. It is the preferred supply mode for high volume and high purity requirements. Membrane systems are preferred because of their lower cost and simplicity for smaller and lower purity requirements [Praxiar, 2007]. Figure 5-18 shows an example of a cryogenic nitrogen production.

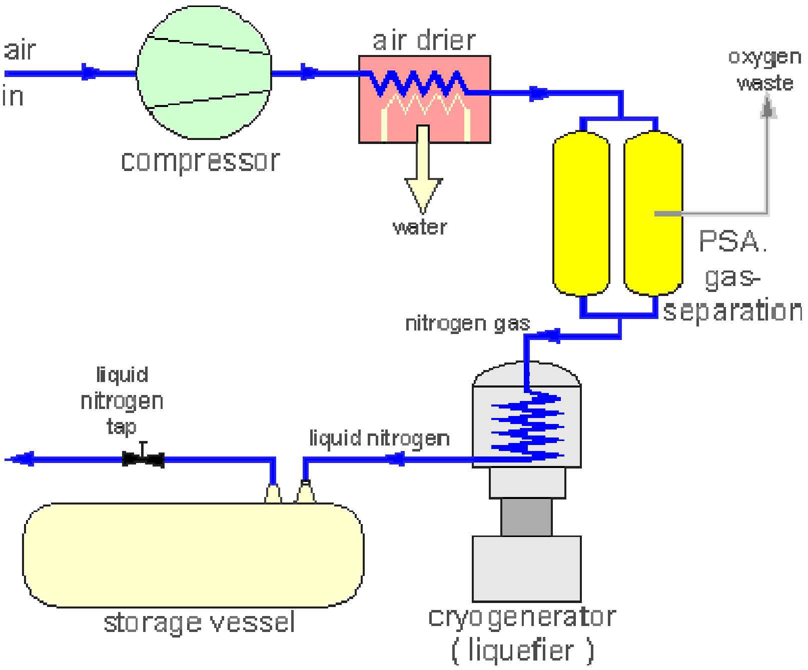


Figure 5-18: Example pf cryogenic nitrogen production [Stilrling, 2007]

5.4.6 CHP with Carbon Dioxide Cleaning

As seen in Figure 2-4 a large part of Norway's possibilities to reduce its emissions of greenhouse gasses is by capturing carbon dioxide and utilizing it in other processes. In the case of combustion processes there are several different processes. Either the carbon is removed from the fuel or nitrogen is removed the combustion air before combustion. In the case of the park being designed, nitrogen is used to produce ammonia, so relatively pure oxygen is available. When using pure oxygen the so-called Graz Cycle gives the basic principle for generating heat and electricity with carbon dioxide capture. It was first presented in 1985 at the CIMAC conference in Oslo, and has been further developed. It has been found economical viable for a carbon dioxide price above 30 $/ton [Graz Cycle, 2007]. Several publications have used the cycle as an example for future gas turbines with carbon dioxide capture [Franco, Mina, Woolatt, Rost, Bolland, 2006; Jericha, Sanz, Göttlich, 2006; Gou, Cai, Hong, 2006].

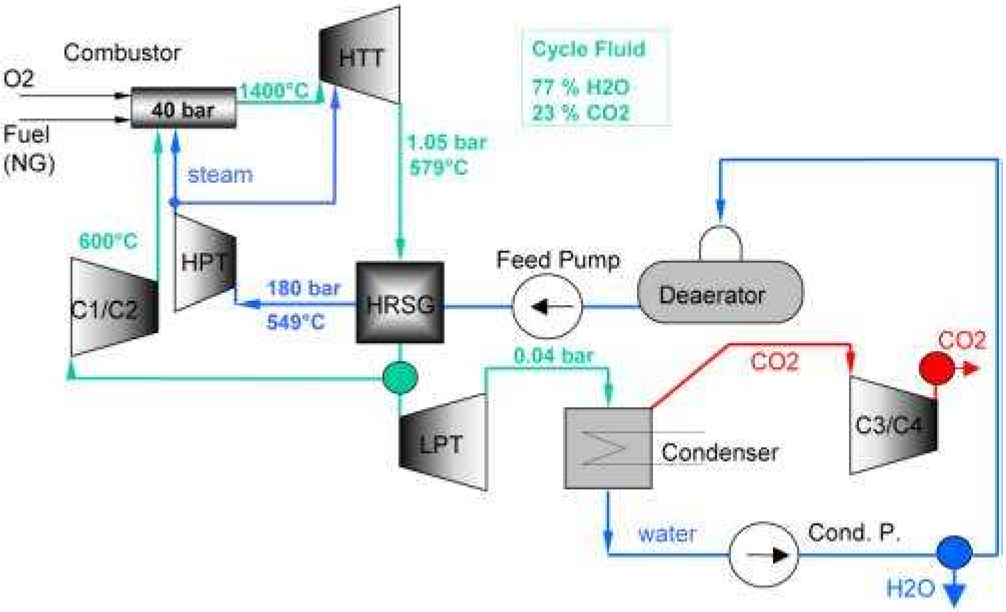


Figure 5-19: Principle flow scheme of basic S-Graz Cycle power plant [Graz Cycle, 2007]

Basically the Graz Cycle consists of a high temperature Brayton cycle (compressors C1 and C2, combustion chamber and High Temperature Turbine HTT) and a low temperature Rankine cycle (Low Pressure Turbine LPT, condenser, Heat Recovery Steam Generator HRSG and High Pressure Turbine HPT). This is shown in Figure 5-19. The cycle arrangement of the Graz Cycle offers several advantages: On one hand, it allows heat input at very high temperature, whereas on the other hand expansion takes place till to vacuum conditions, so that a high thermal efficiency according to Carnot can be achieved. But only less than half of the steam in the cycle releases its heat of vaporization by condensation. The major part is compressed in the gaseous phase and so takes its high heat content back to the combustion chamber. In addition to delivering electricity from the different turbines, heat could also be delivered from cooling the C1/C2 compressor.

6 Simulation

To model the system Aspen HYSYS has been chosen as the simulation tool. To determine what fluid package to be used in the process a method suggested by Carlson [1996] was used. Using the decision process proposed in the paper the SRK (Soave-Redlich-Kwong) package was used. The tool in HYSYS to produce composite curves was chosen not to be used. Instead a tool developed by Industriell Energyanalys AB at Chalmers University, called Pro Pi 1, was used. This program is specially designed to produce composite curves and is en extension for Microsoft Excel.

At first the system was design all in one simulation. This was done to achieve convergence in the system. Then the different systems were simulated by themselves to get a better overview. The system was split into different systems, each of which will be described in the following chapters.

Some processes are not simulated of different reasons. Cleaning of the landfill gas is not simulated due to components needed to clean the H_2S from the gas, and uncertainty connected to the amount of the compound in the land fill gas. Also, the different costumers in the district heating are not simulated. The reason for this is that these only acts as heat sinks in the system, and is therefore only used in the creation of the composite curves. The use of carbon dioxide in the greenhouse is not simulated. This is because the energy needed in the photosynthesis is received from the sun does not effect the system. The urea plant has not been simulated in HYSYS. The reason for this is that ammonium carbamate; a compound in the process is not part of the HYSYS basic package available to the writer. Also, the presence of three phases, and the simulation of these, is beyond the scope of this paper. Instead, the energy and material balances are based on literature studies.

Some assumptions have been made to simplify simulations and to ease convergence in the system, and are idealized in the system. These include:

- Natural gas is assumed to be pure methane
- Input streams are available at 1 atm and 15°C
- There is an unlimited supply of resources to the system
- For the energy and exergy analysis it is assumed that $T_{ref}=T_0=15^oC$

It is assumed that the system operates in steady state. The heat demand in the district heating system and from the laundry will vary over time and the system is certainly dynamic, but a dynamic model of the system is far too complex and comprehensive to be conducted in this project. Therefore different demand scenarios have been created for the different costumers in the low and high temperature heat in the district heating system. Thus the simulation does not take into account sizes of components or their performance with partial loads.

6.1 Steam Reforming and Ammonia Production

Since the syngas is produced only to create ammonia, the simulations have been added together in one flow sheet. Pure methane and water is heated to a temperature of 500°C to begin the reforming process. They are kept at 1 bar and heated to 800°C to produce the largest amounts of CO and hydrogen according to Le Chetalier's Principle. Both the oxygenolysis (equation 5-4) and the water-shift reaction (equation 5-6) goes to equilibrium in the reactor, thus the choice of type of reactor in HYSYS. Next step is to remove the steam from the stream. This could be done by either raising the pressure or lowering the temperature, or a combination of these. In the simulation it has been chosen to lower the temperature. The reason for this is that raising the pressure of high temperature gasses requires a lot of electricity and that the heat could be used in other processes. The steam is then condensed in a flash tank which could produce low temperature heat for the district heating. Both streams are then cooled to surrounding temperature. The remaining gas (stream 9) is compressed to 14 bars for condensation of carbon dioxide. The reason for compressing the gas to this temperature is that the freezing hall could cool the gas to -35°C, providing a condensation pressure for carbon dioxide of 11.84 bars. The extra pressure has been added to ensure good conditions for the separation. The condensed carbon dioxide is added with the other carbon dioxide streams for urea production. The remaining hydrogen-rich gas is compressed to 200 atm for the ammonia process. The ammonia process is highly simplified in the simulation. It is beyond the scope of this paper to simulate a detailed ammonia production. So based on literature [EFMA, 1995], the process has been simulated using a conversion reactor with a 97 per cent conversion of nitrogen. Since the gas now has high pressure and temperature, and the temperature should be lowered to purify the ammonia, the gas is sent through a gas turbine. Thus, electricity is produced in the process of lowering pressure and temperature of the gas. The gas is then cooled just above ammonia's boiling point before being sent into a condenser, providing a yield of pure ammonia for the urea plant. The remaining gas is composed of un-reacted hydrogen and CO. This gas is combusted to provide heat in the system.

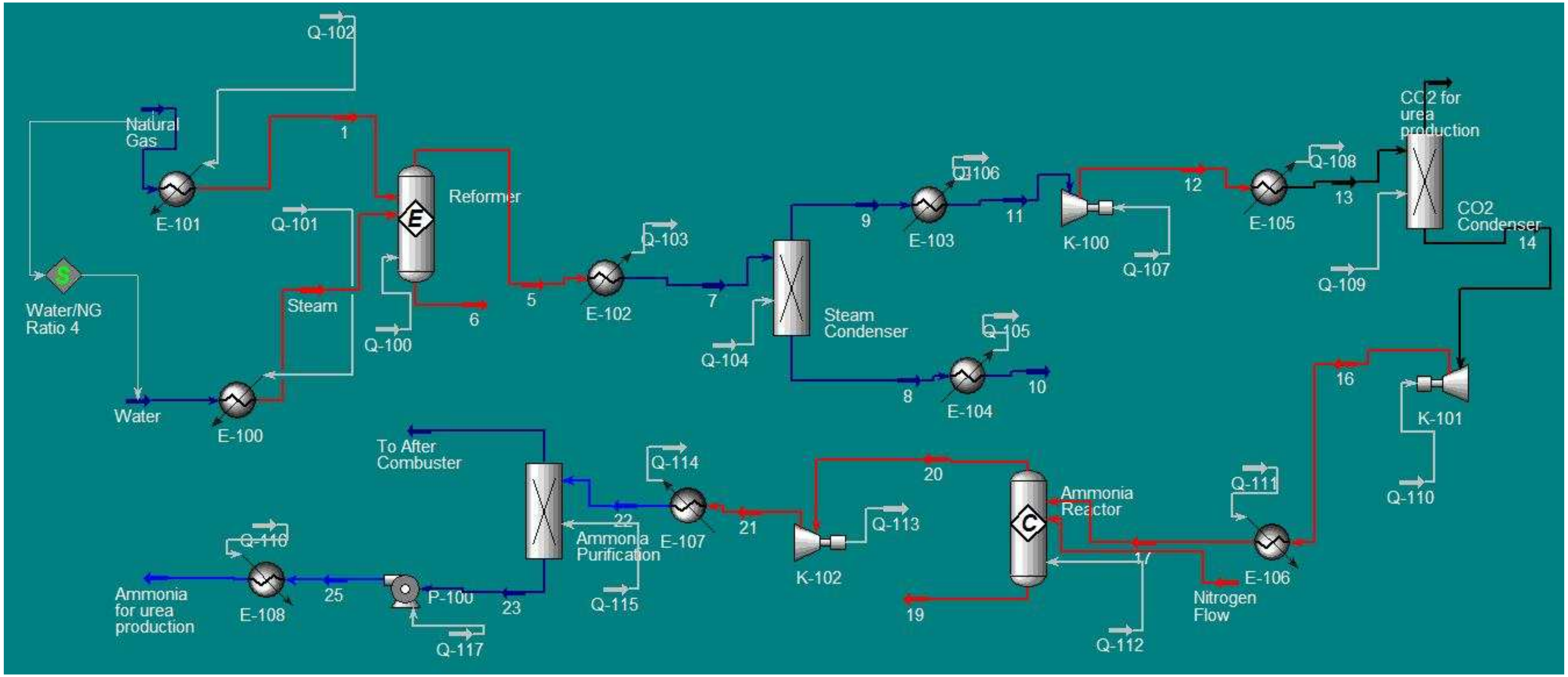


Figure 6-1: HYSYS flow sheet of syngas and ammonia production

6.2 CHP with Carbon Dioxide Cleaning

Two models were built for the energy-production with carbon dioxide cleaning. First, a model based on the basic Graz Cycle presented in chapter 5.4.6 was designed with the given specifications. This cycle proved to have a very low electric efficiency, but with a total efficiency in the range of other CHPs. Thus, a second model was developed. The goal of this model was to raise the electric efficiency. The new design was based on a pilot plant study [Heitmeir, Sanz, Göttlich, Jericha, 2003]. It provided more then double the electric efficiency, but a lower total efficiency as it delivers no heat to the system. To evaluate which of the designs should be used in the system, the energy unit was kept “outside” of the system. Meaning; the rest of the system was developed without any heat exchange with the energy unit. Since the system showed a lack of heat, the CHP was chosen over the high electric efficient design. The reason for this is that heat should be by-product in an EIP. If the el-efficient design had been chosen a boiler would have had to be installed. Both energy and environmental considerations were taken. But because of the comprehensive work connected to analysing energy and exergy flows in a system this complex, this choice is based on qualitative, not quantitative analysis. The design is shown in Figure 6-3, while the CHP model used in the system is shown in Figure 6-2 and described below.

Pure methane from the landfill gas is compressed to operating pressure of 40 bars and enters the combustion chamber where it reacts with pure oxygen from the air splitter. The oxygen is pressurized in liquid form and delivered at ambient temperature. The combustion chamber is presented by the equilibrium reactor and the mixer MIX-101. This separation has been done since the added streams of flue gas and steam has no effect on the reaction. They are added to the stream to lower the temperature in the combustion chamber for material purposes and to increase the material flow in the turbine to produce more electricity. The amount of both flue gas and steam has been manually iterated. This was done to ease system convergence. These flows are subject to three different demands; temperature out of the combustion chamber, flue gas fraction recycled and water fraction entering the turbine. The recycled flue gas stream entering the mixer is the same as stream 2 in the upper right corner of the sheet. Opening up the original loop in the system helped the system converge and eased the simulation. Steam is added to the flue gas into the turbine to produce more electricity. The flue gas is then used to evaporate and super-heat the high pressure recycled water in the heat exchanger. The flue gas is then split in two, 55 per cent being compressed and recycled to the combustion chamber, while the rest will be expanded to almost vacuum. Water is then condensed out of the flue gas, leaving an almost pure carbon dioxide gas. Part of this is sent to the greenhouse, while the rest of the carbon dioxide gas is compressed to 14 bars to be liquefied in the freezing hall. The condensed water is split into waste water and water to be recycled back into the process. The recycled water is pumped to a pressure of 180 bars and subsequently heated in the heat exchanger. Before entering the combustion chamber mixed with the flue gas, the high pressure super-heated steam is expanded in a high pressure turbine to produce electricity. The energy balance spread sheet connected to the simulation is used to evaluate energy efficiency in the process.

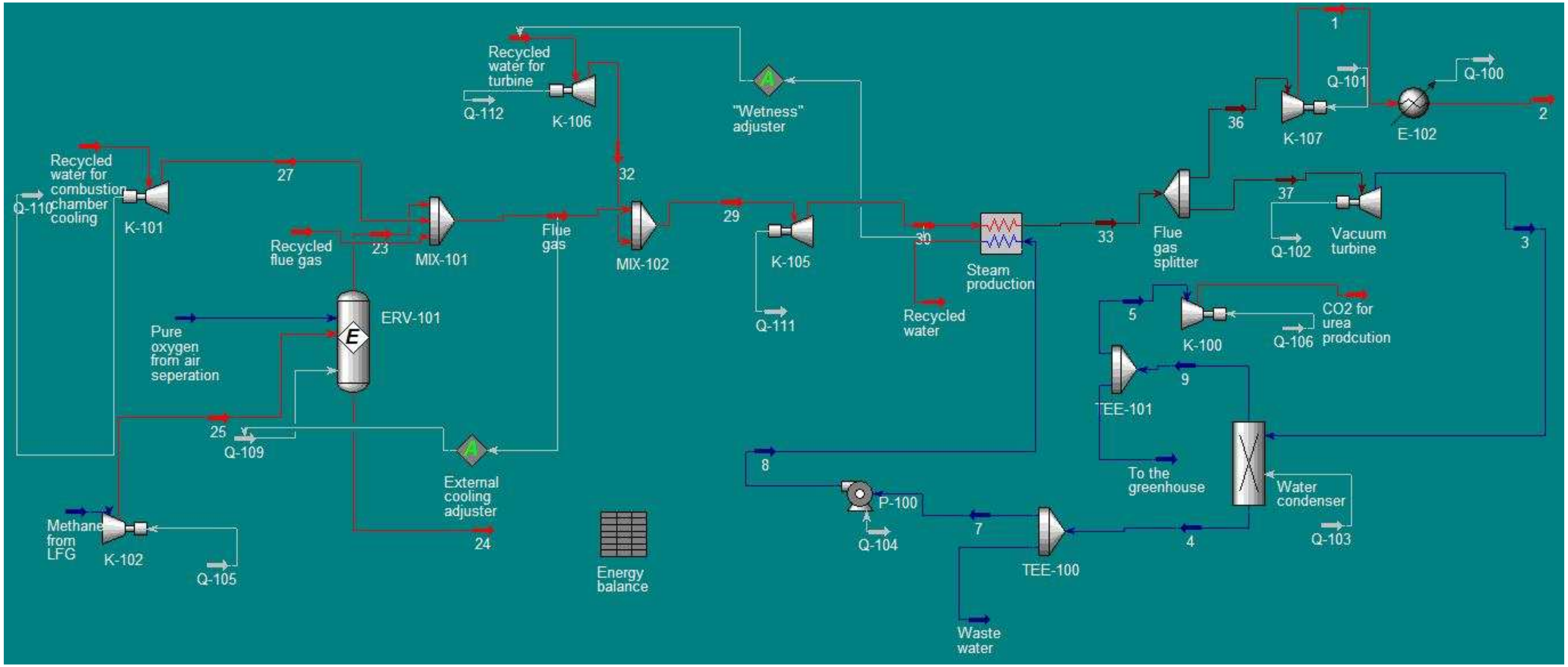


Figure 6-2: Combined heat and power with carbon dioxide capture flow sheet

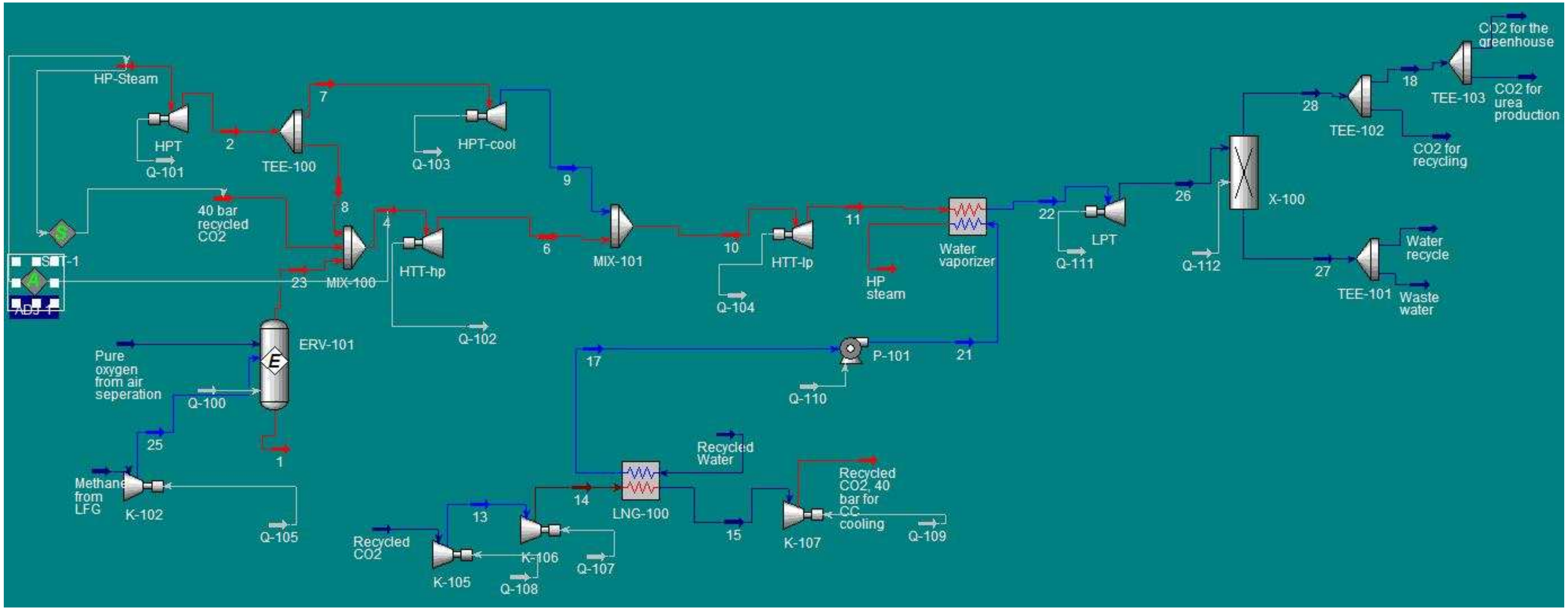


Figure 6-3: High electric efficiency design

6.3 Air Separation

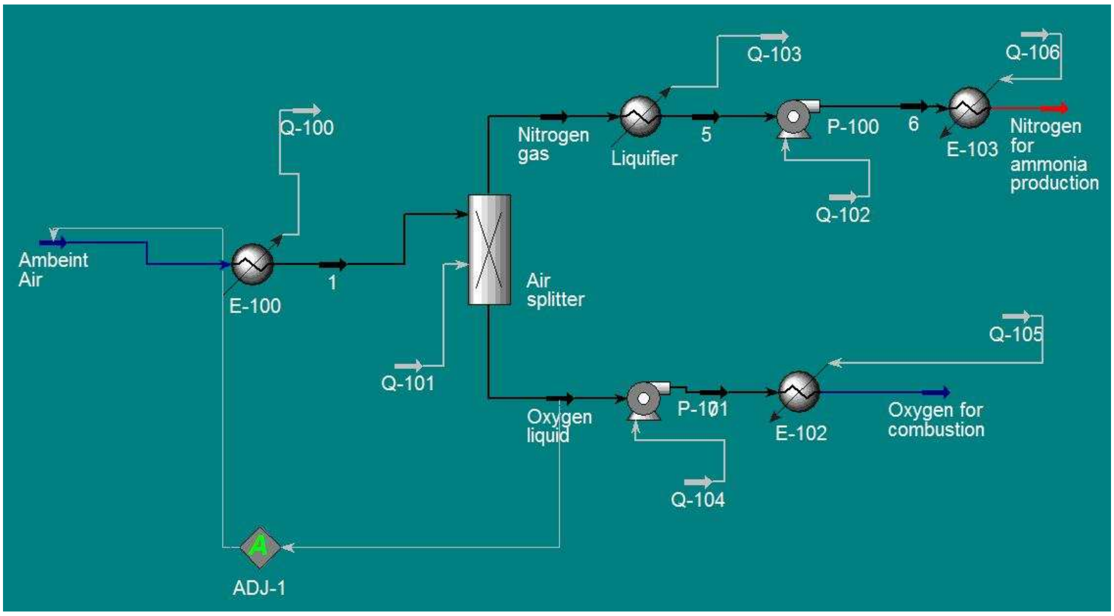


Figure 6-4: Air separation flow sheet

A cryogenic separation of air is chosen. To simplify simulation, air is presented as 21 per cent oxygen and 79 per cent nitrogen. It has been chosen to separate the gasses at ambient pressure. Several different procedures exist, but to minimize compressor work ambient pressure has been chosen. Oxygen has higher boiling point then nitrogen at 1 bar and is thus liquefied first in the air splitter. The liquid is then pressured to 40 bars to be combusted in the Graz Cycle, and the temperature is raised to ambient temperature. The nitrogen gas is then further cooled and liquefied. The reason for doing this is that nitrogen should enter the ammonia production at 200 atm and compressing liquid requires much less work then gas. The pressurized nitrogen is subsequently heated to 450°C for ammonia production.

6.4 LFG Splitting and CO_2 Collection

Based on the presence of the freezing hall a condensation pressure was set. The landfill gas is therefore compressed to this pressure before being cooled down in a heat exchanger. The mixture is then separated as the carbon dioxide is condensed. The methane is sent to the CHP, while the carbon dioxide is mixed with the other sources of carbon dioxide to be used in the production of urea. The stream from the CHP needs to be cooled before it is further processed. It also contains a fraction of oxygen, which is removed in the condensation process. When condensed, the carbon dioxide is mixed with the other streams for urea production. The total carbon dioxide stream is compressed to 150 bars to be used in the production of urea. Figure 6-5 shows the simulation flow sheet.

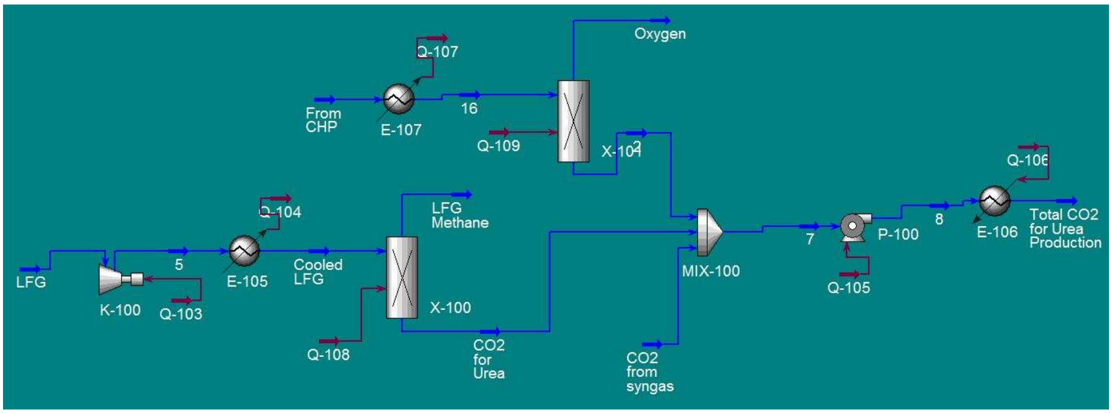


Figure 6-5: LFG split and CO_2 mix flow sheet

6.5 Utilities

The remains from the ammonia production consist of hydrogen and carbon monoxide and are combusted to provide heat for the system. The flue gas produced is of high temperature and used as a heat source in the system. Analysis of the system showed that the system was in need of 130°C steam and direct fuelling of the syngas reformer. The loop in Figure 6-6 shows the production and use of this steam. The steam is solely produced by units in the system. The remaining utility proved to be heating the reformer. Therefore a dedicated heater for the reformer is constructed, adjusted to deliver the remaining heat needed at the reformer.

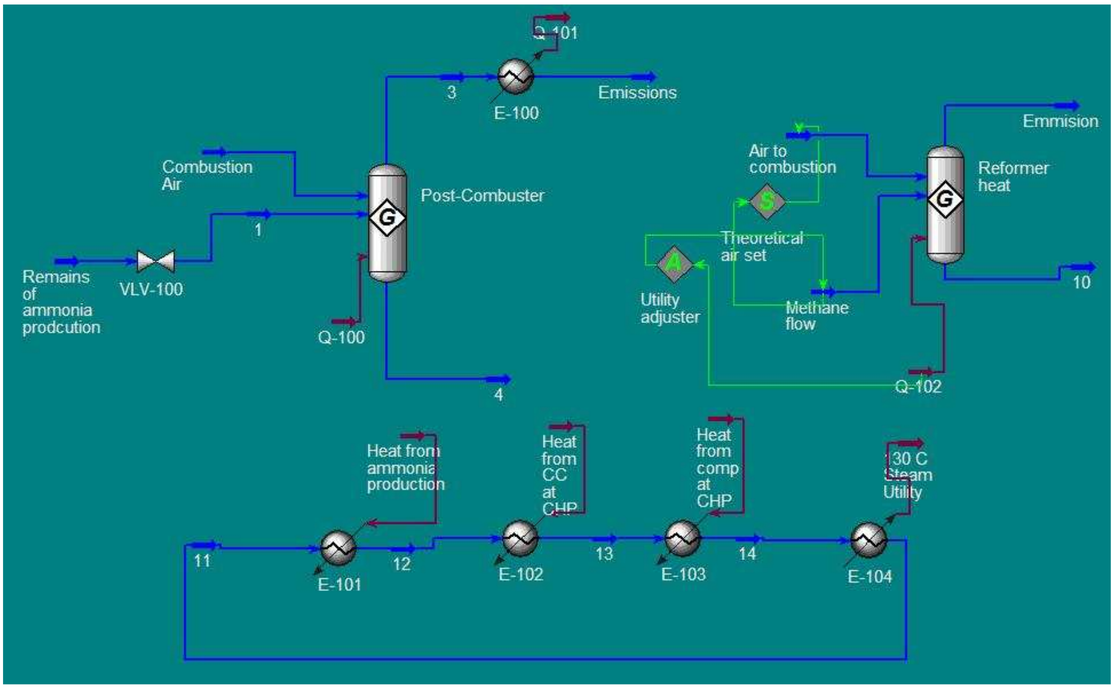


Figure 6-6: Utilities for the system

6.6 Urea Production

Since the urea production was not simulated in HYSYS a study was made to provide quantitative results for the production. There is presently no adequate tool to provide correct results for urea modelling. For the purpose of evaluating the performance of the EIP, the urea production needs only to be considered as a black box. The black box will provide the system with energy and mass balances. For material balance results from a model proposed by Zhang, Zhang, Yao and Yuan [2005] is used. For energy considerations experimental data found in reports are used [Joncich, Solka, Bower, 1967; Claudel, Brousse, Shehadeh, 1986]. Based on the equations given in chapter 5.4.3 Zhang et al. [2005] found the highest conversion of carbon dioxide to be almost 80 per cent, and this will be used in the black box modelling. Other sources report of 100 per cent material efficiency [EFMA, 1997], but provides no specific case studies or models. Energy use in urea production is well known. Joncich et al. [1967] provided reaction energies for both the fast exothermic, and the slow endothermic equations, and this is confirmed in later work by Claudel et al. [1986]. The formation of ammonium carbamate is exothermic; releasing 159 kJ/mol^{-1}. The slower and restrictive dehydration of ammonium carbamate, producing urea and water, requires 23 kJ/mol^{-1}. Steam produced when the urea is dried is sent to the laundry.

6.7 Flow Analysis

To calculate the energy and exergy flows from the simulation several sources have been used. Temperature and pressure dependant values of energy and exergy have been extracted directly from HYSYS. A excel program has been written by Rahul Anantharaman at the Department of Energy and Process Technology, NTNU, that extracts data from HYSYS. To evaluate the energy flows, the higher heating value has been used. Calculations have been made according to equation 4-10 in chapter 4.1. To find the higher heating value for ammonia the reaction shown in equation 6-1 was used.

$$\frac{3}{2}O_2 + 2NH_3 \rightarrow N_2 + 3H_2O \qquad \textbf{6-1}$$

The chemical exergy of each compound is found in model II in table A-31 in Moran and Shapiro [1998]. It is derived from J. Szargut, D. R. Morris, and F. R. Stewart *Exergy Analysis of thermal, Chemical and Metallurgical Processes* from 1988. In the model P_0=1atm and a reference substance is selected for each chemical element from among substances that contain the element being considered and that are abundantly present in the natural environment. But the equilibrium criterion is not always satisfied. This model is widely used in engineering problems. It should be noted that neither chemical exergy nor higher heating value is found for urea.

Since the system is large and complex it has been divided into three different parts for the energy and exergy analysis. The syngas/ammonia and CHP cycle are evaluated separately and used as black boxes in the last flow sheet of the total system. The urea production is not simulated but is included in the flow analysis as a black box. When drawing the flow sheets of exergy, the exergy losses are not drawn directly into the system. This has been done since there is a certain degree of uncertainty connected to several of the losses. These are instead explained and partly quantified in the text. For the MFA it has been chosen to focus on the flow of carbon in the system. Developing a total heat exchanger for a system this size is beyond the scope of this paper and is thus not conducted. The flows exchanging heat are presented by composite curves. This gives quantitative results for the exchange and use of utilities.

Table 6-1: Higher heating values and chemical exergy

Substance	HHV (kJ/kmol)	Ach (kJ/kmol)	Ref env. Fraction (y^e)*
O_2	N/A	3970	0,2014
N_2	N/A	720	0,7478
CO_2	N/A	19870	0,0003
$H_2O(l)$	N/A	900	N/A
$H_2O(g)$	N/A	9500	0,0216
CO	282990	275100	N/A
H_2	285830	236100	N/A
NH_3	382705	337900	N/A
CH_4	890330	831650	N/A

*: y^e is derived using equation 4-9

Based on the flows in the system, an environmental assessment has been conducted. The total emissions of greenhouse gasses from the system are compared to the emissions from stand alone units. Data for the stands alone units has been found using Simapro 7.0.2, a tool developed to conduct life cycle assessments (LCA). The "Ecoinvent Unit Processes"-library has been chosen as the data source for the unit processes. The library contains life cycle inventory (LCI) data from several sectors, with a total of 2500 datasets. In such datasets, the emissions and use of materials are defined by a functional unit. The functional unit could either be a product or a service. For instance; the functional unit could be 1 kWh of electricity. How this electricity is produced determines the use of material and emissions.

7 Results

The complete results for the simulation are given in different appendices. The main results are presented in this chapter. Firstly, general results are presented, followed by results of the flow analysis.

7.1 General Results

- The system produces 1015 kg of urea each hour.
- The CHP has an electric efficiency of 27 per cent and a total efficiency of 73,8 per cent.
- Electric exergy efficiency of the CHP is 28 per cent with a total system exergy efficiency of 67,7 per cent.
- Total greenhouse gas emissions are 994 kg of CO_2 each hour, a total of 7948 tons each year.
- To cover the total heat demand of the system, a extra flow of 46.21 kg of methane is added to the system. This is used to heat the reformer.

7.2 Heat Exchange

The laundry was left out of the heat exchange composite curves. This was done since it was thought that it would only raise the demand for heat. It proved a wrong assumption as the heat from the urea production could produce more then enough steam for the laundry. The composite curves are shown in Figure 7-1.

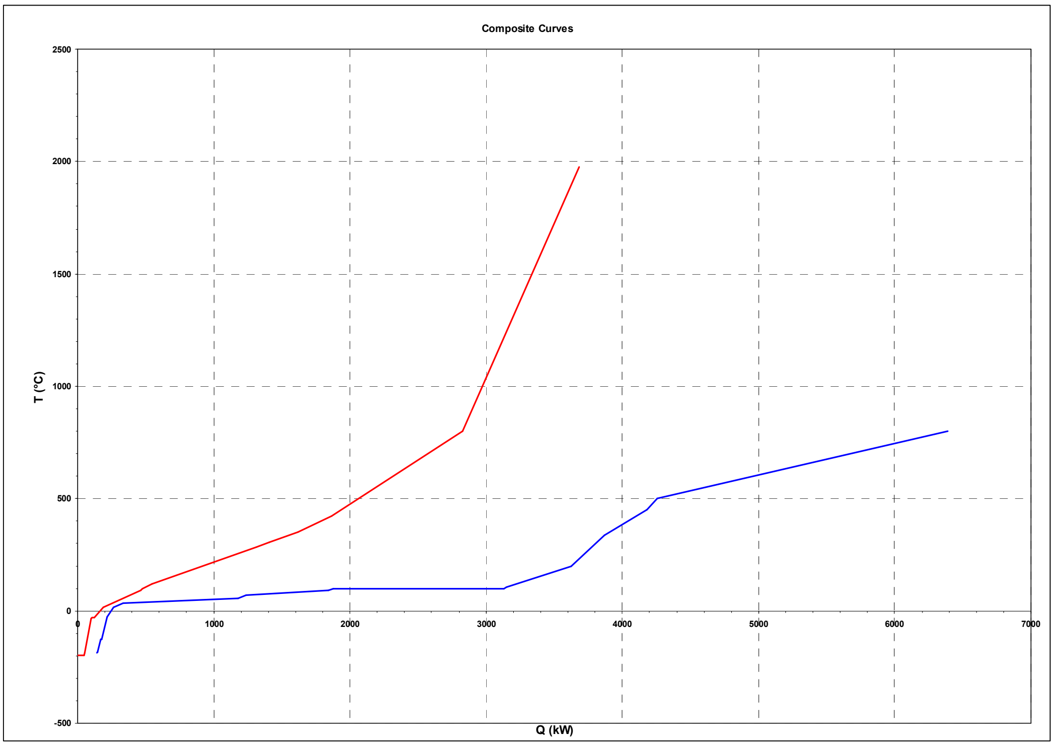


Figure 7-1: Composite curves for the system

As the composite curves show, there is a total need of 2712.42 kW of hot utility and a total need of 143.22 kW of cold utility. Since the cold utility is needed at very low temperatures it must be provided by electricity of a cryogen process. For the system it is chosen to be covered by electricity. To determine how the hot utility could be covered, the grand composite curve was created. This is shown in Figure 7-2. The low temperature area is covered by the condensation heat form the heat pump installed at the freezing hall. The gray areas are pockets, where the system provides enough heat to cover the utility itself. The next level is mainly the steam for the syngas production. Water is pumped to 3 bars to and is then passed through different components in the system to produce steam at 130 degrees. The heat is delivered by the ammonia reactor, the combustion chamber of the CHP and the compressor cooling from the CHP. Together they produce more then enough heat to cover the demand. The production of syngas is endothermic and is also a high temperature reaction. This is covered by some of the flue gas from the post combustion of the remains from the ammonia production. This is the area covered by the rightmost pocket. In addition, the reformer is directly fired by methane.

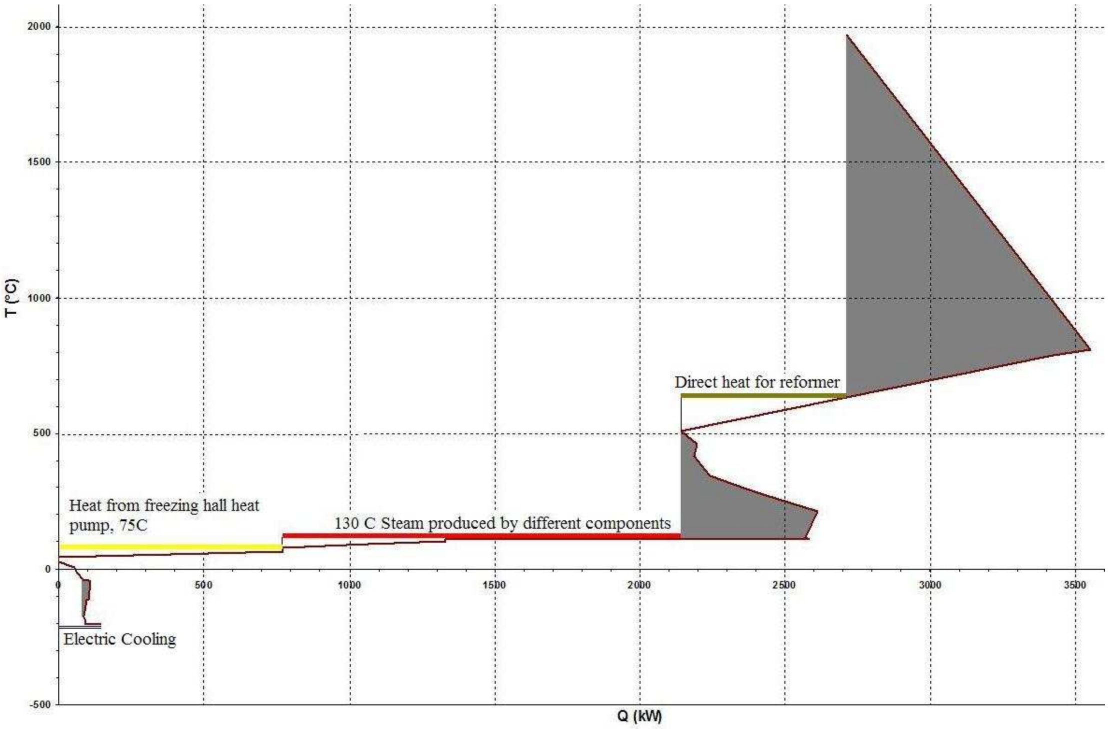


Figure 7-2: Grand Composite Curve for the system

7.3 MFA

A material flow analysis of the carbon in the system was conducted. The qualitative flows are shown in Figure 7-3. It shows that the largest source of CO_2 emission is the remains of the ammonia production. Most of the carbon dioxide in the system is used to produce urea. Since a conversion rate of 80 per cent is used, the urea production also produce some carbon dioxide emissions.

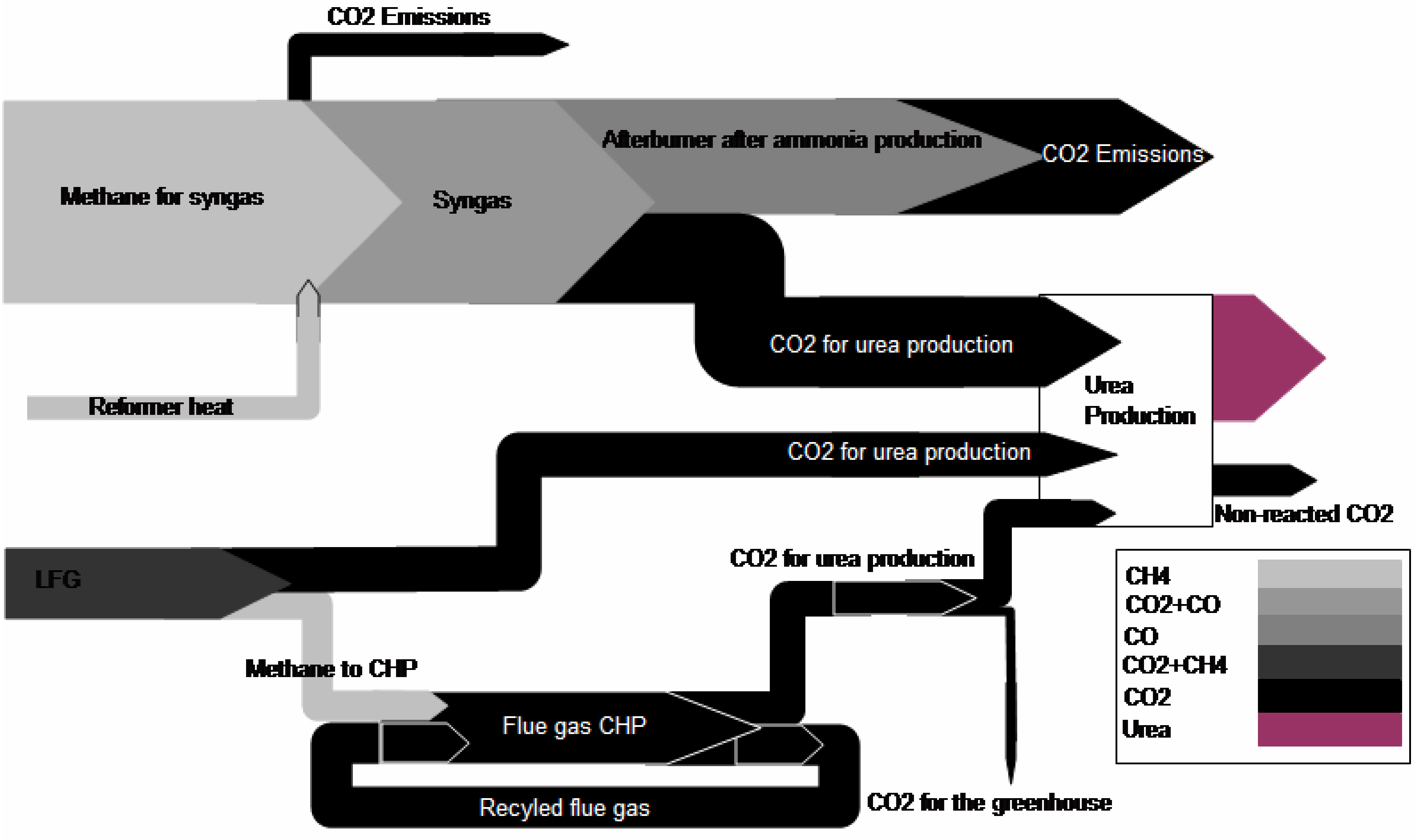


Figure 7-3: MFA of the system

7.4 Energy Flow Analysis

The three parts of the energy flow analysis are shown in Figure 7-4, Figure 7-5 and Figure 7-6. The flow sheets will not necessarily total energy balances, since some streams also containing some amount of energy is excluded to simplify an already complex flow sheet. This is especially the case for the system flow sheet. In this sheet only the flows relevant for the system has been included. Since there is a large uncertainty connected to the energy content in urea and the waste water from the production these are not quantified. In the sheets some of the flows are denoted by stippled edges. This is done to illustrate flows with either no energy or negative energy. Flows with negative energy is a result of the choice of setting T_{ref}=15°C. Since several of the flows operate below this temperature they will contain “negative” energy. As a general note electrical work delivered are coloured black, heat transfers are red and electricity flows are gold. It is also worth mentioning that in both the ammonia flow sheet and CHP flow sheet the different flows are in scale. This is not the case with the system flow sheet. In the system flow sheet the air split has one scale and the LFG cleaning has another. The rest of the flows in the system are not in scale.

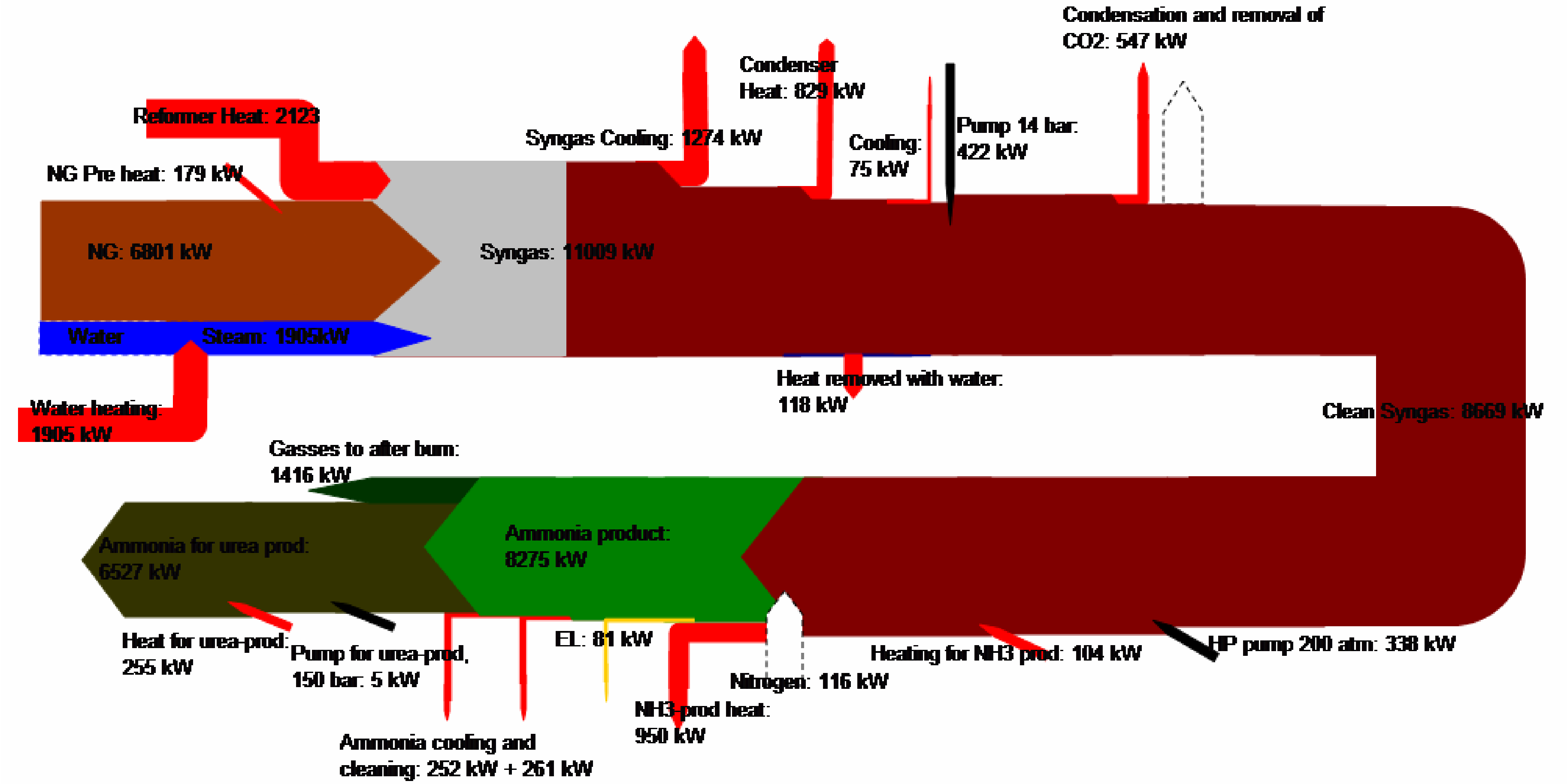


Figure 7-4: Ammonia Production Flow Sheet

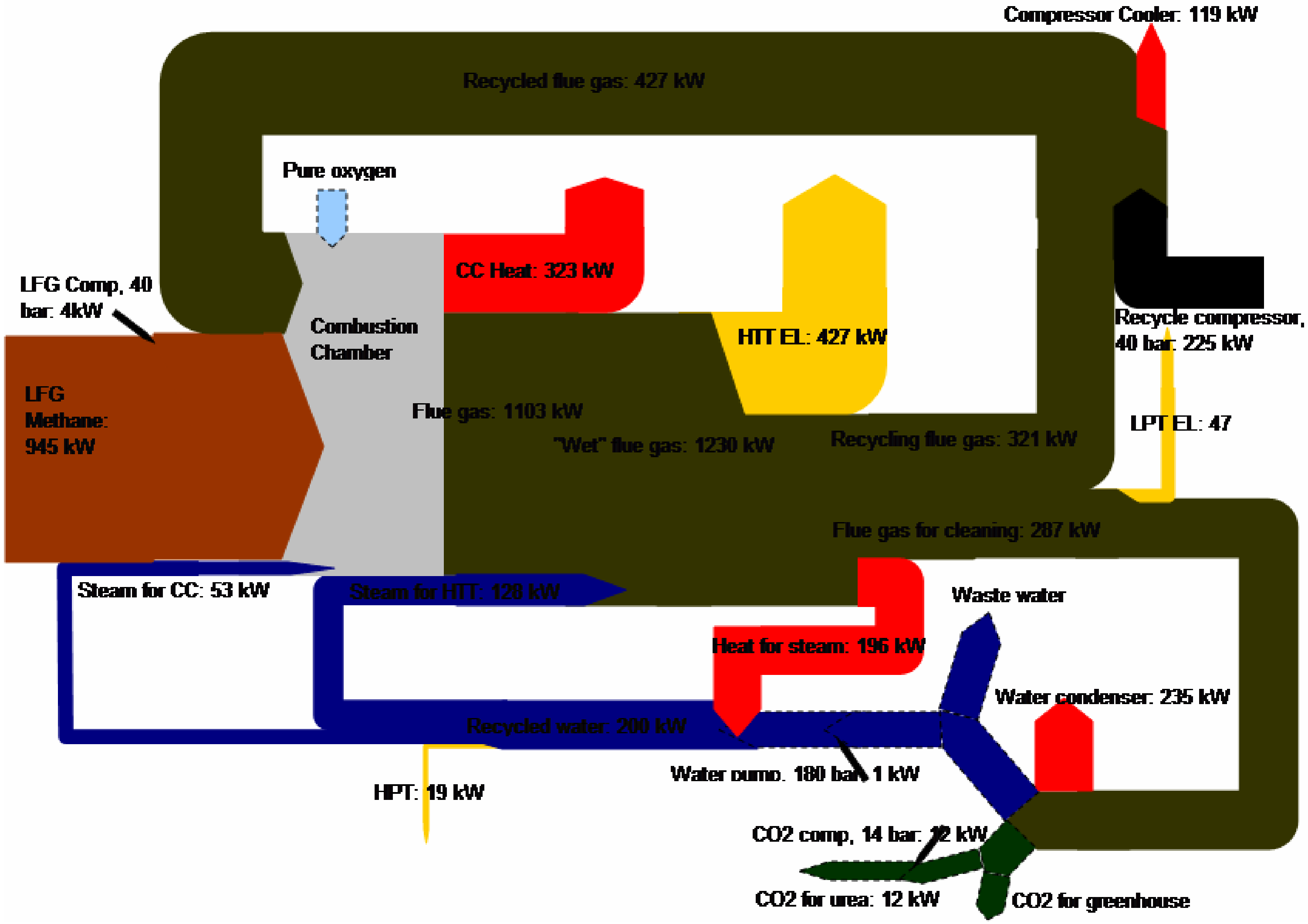


Figure 7-5: CHP Energy Flow

]

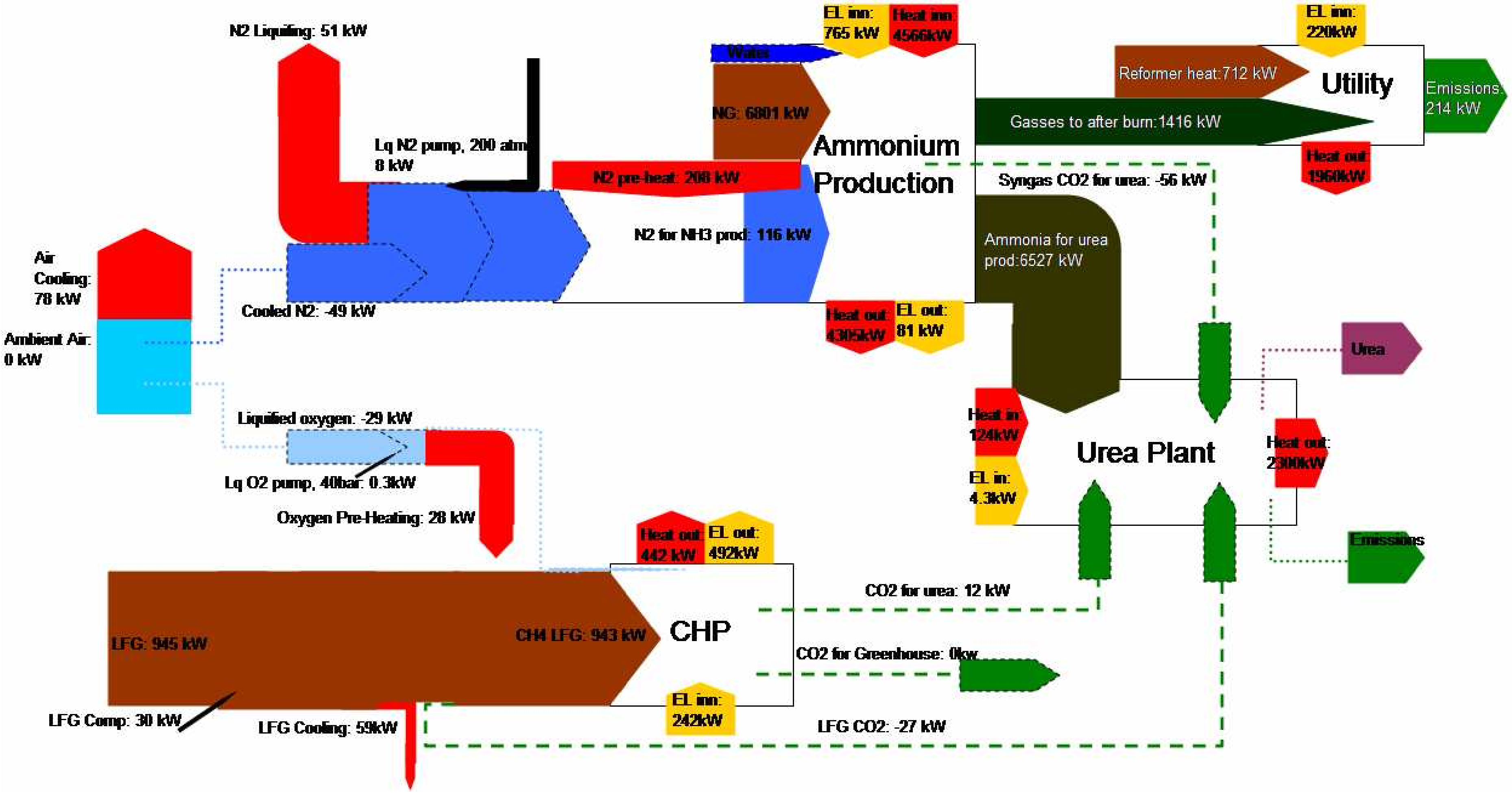


Figure 7-6: System Energy Flow

7.5 Exergy Flow Analysis

The three exergy flow sheets are shown in Figure 7-7, Figure 7-8 and Figure 7-9. The flows are based on exergy balances between flows. Thus, the flows of heat or work into the flows will include the exergy loss due to irreversibility. As for the energy flow sheets, only the first two are in scale, while the system exergy flow sheet is not. The results for the exergy flows are somewhat misleading, and the manor that it has been conducted is discussed in the following section.

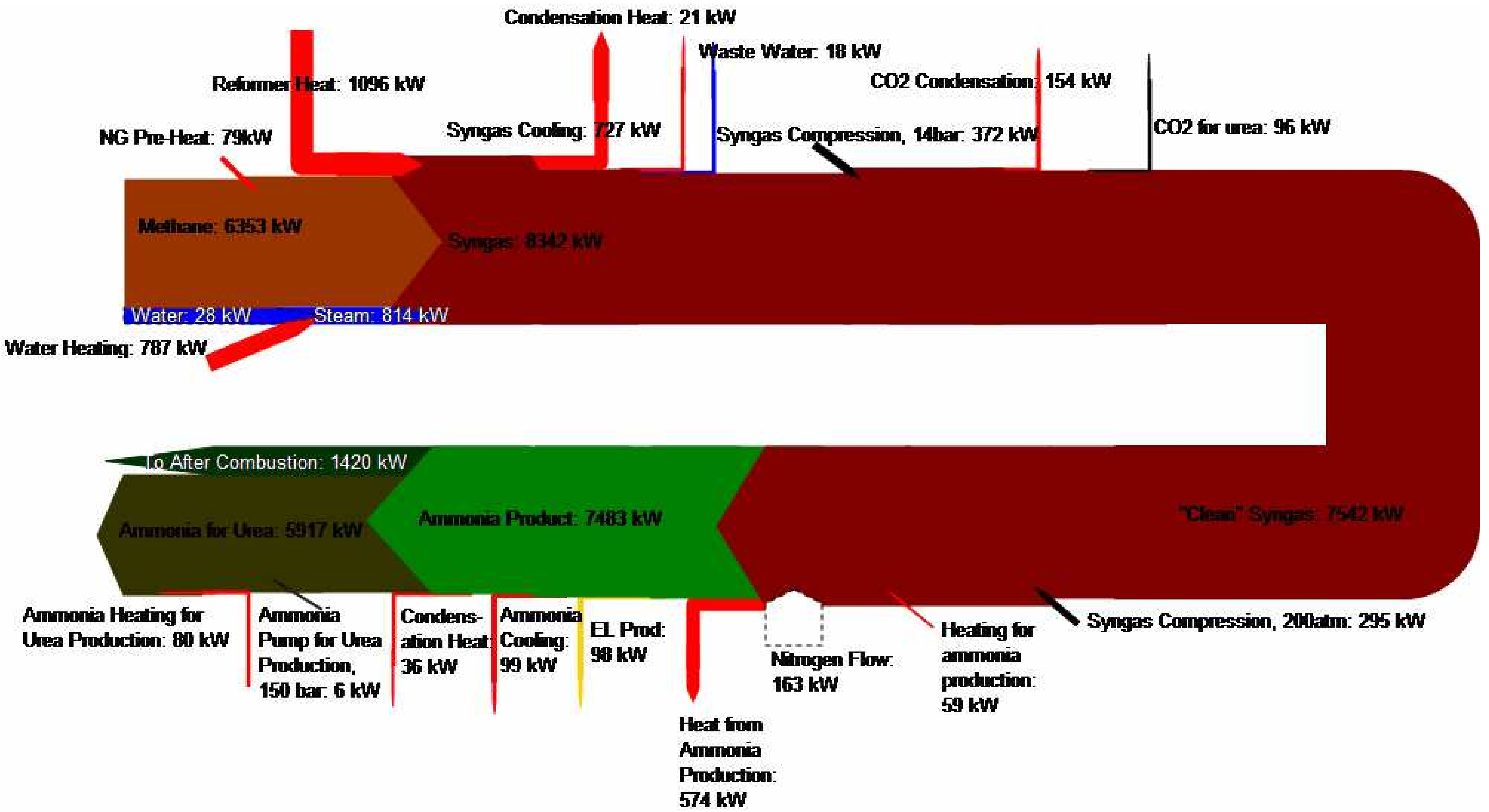


Figure 7-7: Ammonia exergy flow sheet

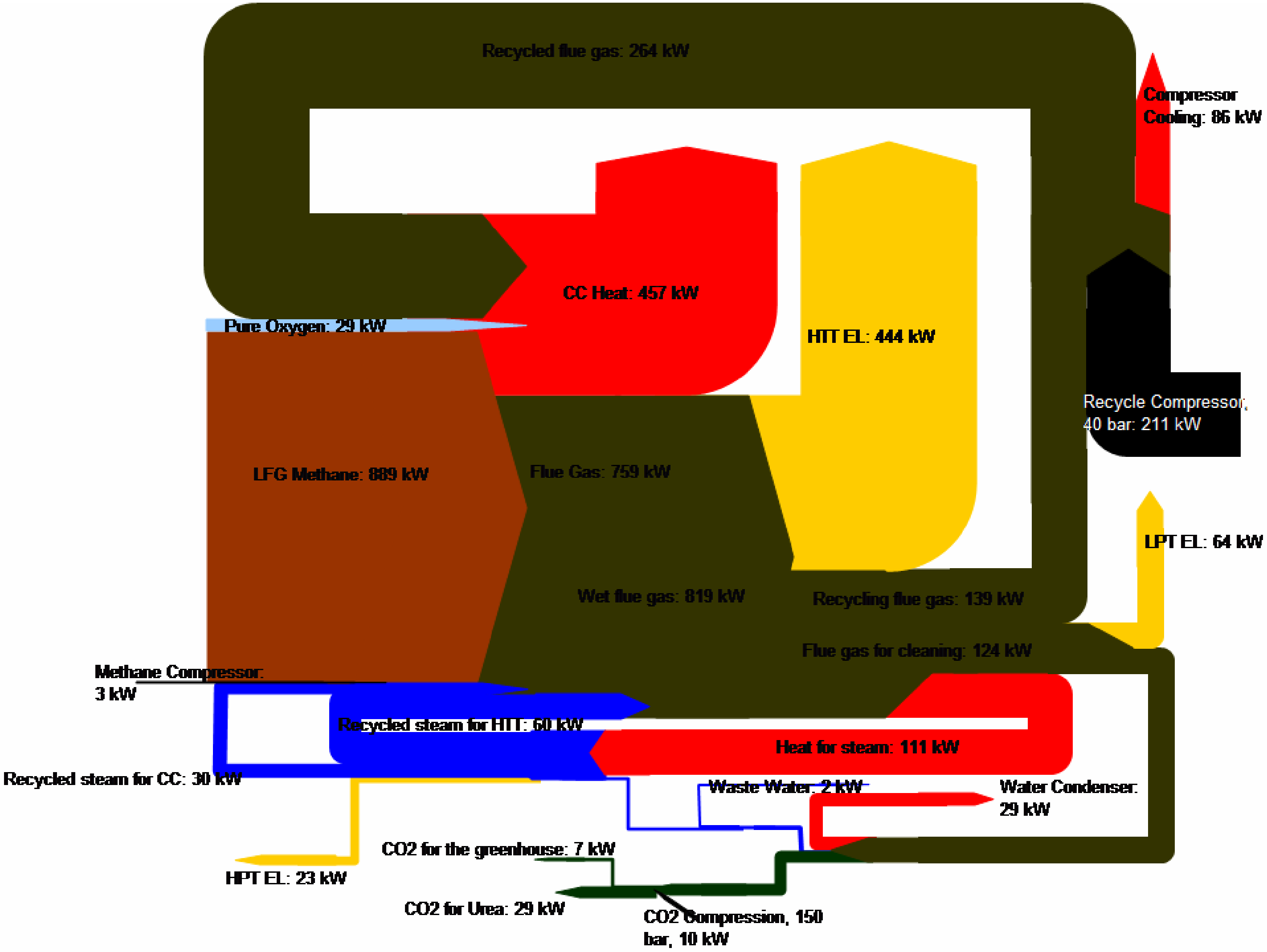


Figure 7-8: CHP exergy flow sheet

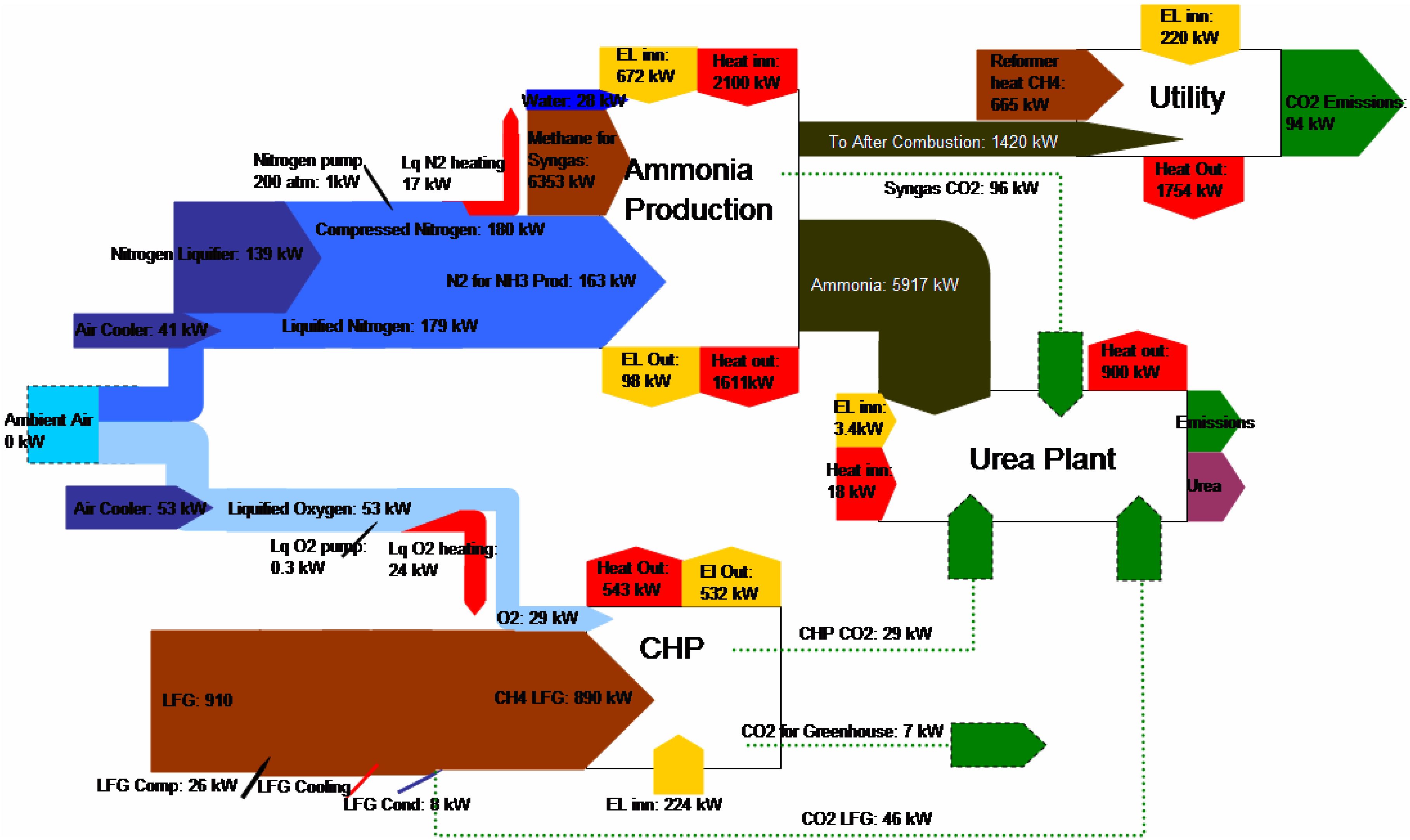


Figure 7-9: System exergy flow sheet

8 Discussion and Conclusion

8.1 Heat Exchange

The choice of not including the laundry could have been avoided if the urea process had been better understood when the heat exchange system was developed. On the other side, including it from the start could have resulted in several sources of heat for the steam. As the grand composite curve shows the steam produced at the laundry would have ended up in the small pocket, but not totally covered, thus needing several sources of heat. Now the steam will solely be produced by the urea reactor. This is logic if one considers both technical and economical factors. Producing pressurized steam from several sources of heat using several heat exchangers requires more complex technical installations then one exchange between a reactor and a pressurized stream. Also, heat exchangers are subject to the economy of scale, meaning that each extra kW is cheaper with size, thus several small heat exchangers would be more costly then one large heat exchanger.

A network of heat exchangers showing which streams exchange heat has not been developed. This is a comprehensive work and beyond the scope of this paper. The drawback of this is that it is hard to determine where the flows of energy flow. Practically it is more feasible to have most of the exchanges within each process. However, the aim of using the composite curves in this paper has not been to develop heat exchanger networks, but to use it as a tool to quantify sources and sinks of energy in the system.

The district heating demand will vary over the year and thus variation is hard to intercept in these curves. Therefore, the heat demand for the high and low temperature district heating has been chosen at the level covered by the original system currently being developed.

Steam at 130 bars is produced from three different sources. This is in conflict with the argumentation for not doing this with the steam at the laundry. And a total utilization of the heat from these components is maybe not realistic. However, there are two factors supporting the choice. Firstly; the three sources of heat could provide more energy totally then is used to produce the stream, the heat not being utilized could be considered heat loss. Secondly; the utility shall deliver heat to more then one heat sink as in the case of the laundry.

8.2 MFA

The basic material flow analysis was conducted to trace emissions of greenhouse gasses emitted from the system. To evaluate how the system performs environmentally it should be compared with stand alone processes delivering the same amount of product. Ideally, an LCA with the urea produced as a functional unit should be conducted. However, a well developed LCA is a comprehensive task way beyond the scope of this paper. Instead the emissions of stand alone units producing three products have been used. Emissions for producing 2 GWh of electricity produced form natural gas, 8312 tons of ammonia and 8120 tons of urea has been calculated. The results are shown in Table 8-1. It shows that the system releases 35 per cent less emissions compared with stand alone units.

Table 8-1: Emissions from stand alone units

Product	Unit Emission	Total Emission
Ammonia	1.46 kg/kg	12136 ton
Urea	0	0
El	0.0552 kg/MJ	397440 kg
Total emission		12533 ton

8.3 Energy Flow Analysis

The energy flow analysis has proven to be a good tool for tracking energy in a large system such as this. The quantities calculated for use in the flow sheets show very good coherence with data in the simulated models in HYSYS. When calculating energy flows, engineers often use lower heating value. This is because the heating value is commonly used in when calculating systems including combustion. And in such processes the condensation heat of water is seldom utilized. When using the lower heating value, the energy flows proved to vary greatly with the sizes in HYSYS. The switch to using higher heating value proved to solve this.

The analysis shows that the system is in need of large quantities of electrical energy. There are two main reasons for this need. Firstly, the cleaning of carbon dioxide at the chosen temperature requires a pressure of 14 bars. Compressing gases require large amounts of energy but also heats the stream. In the system, which originally was in need of heat, it has been chosen to cool the gasses separately from the compression. This choice could be seen as wrong, as the system actually has too much heat available at most temperatures and the need of electrical work needed to be added. However, the design of components has not been the focus of this paper. The second reason for the large need of electricity is that both the two large processes, namely the ammonia and urea plants are high pressure processes. In the urea process this has been severely reduced since the carbon dioxide and the ammonia is available as liquid. Pressurizing liquid requires far less energy then compression gasses.

The use of $T_{ref}=T_0$ provided several streams with negative energy. In the analysis this has not provided a problem, thus showing that the reference state could be set arbitrary when only changes in energy is interesting. For gasses, 0K is often used as a reference state.

8.4 Exergy Flow Analysis

Whilst the material streams in the energy flow sheets are based on data for each stream, the flows of heat and work is based on the change between input and output data. In the case of the energy slows this provides no problems when heat loss is neglected. However, this is not the case of exergy. As shown in equation 4-3, the change of exergy is subject to irreversibility. For the flow of electric energy this irreversibility could easily be found as electric energy is 100 per cent exergy. Thus, it could be seen that the irreversibility in the high temperature turbine is 17 kW, or about 4 per cent of the change in exergy. This is however not no straight forward when evaluating the heat transfers. . If the heat transfer happens between two streams at fixed temperatures the integral is removed and the transfer could be written as in equation 8-1. Following this, the loss of exergy could be found using equation 8-2. However, most of the heat exchanged in the system is exchanged between streams of varying temperature.

$$\mathrm{E}^{\mathrm{Q}} = \mathrm{Q}\left(1 - \frac{\mathrm{T}_0}{\mathrm{T}}\right) \tag{8-1}$$

$$\dot{I} = \dot{E}_1^Q - \dot{E}_2^Q = \dot{Q}\left(1 - \frac{T_0}{T_1} - 1 + \frac{T_0}{T_2}\right) = \dot{Q}T_0\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{8-2}$$

This has led to complicating the loss of exergy in the exchanging of heat. From the composite curves shown in Figure 7-1 it could be seen that there is quite a large difference between the temperatures on the warm side compared to the cold side. Thus, the loss of exergy due to heat exchange would be quite large. With the analysis suggested in this paper, these losses will not be identified. To evaluate these losses, each source and sink in the heat exchange must be determined, thus creating a network of heat exchangers. Also a model on how the heat exchanged with heat must be developed. This development is beyond the scope of this paper, but developing a tool to determine these losses would be interesting work for future projects.

One exergy analysis of particular interest is however feasible; the system's exergy efficiency. Since electricity is produced and the heat delivered is delivered from sources with constant temperature, the framework presented in this paper could be used. Both the combustion chamber and compressor cooling heat is used to condense the steam used as a utility in the system. Assuming the components has the same temperature as their outflows, the combustion chamber and compressor delivers heat form 1400°C and 600°C respectively. Using equation 8-1 an exergy efficiency of 67,7 per cent. This is interesting since the choice of using a CHP instead of the high electric efficient Graz Cycle has proved to give higher efficiencies in regards to both energy and efficiency, which is not always the case when evaluating exergy.

8.5 General Discussion

The scope of this project has been to develop the industrial symbiosis at Mosseporten. Using the guidelines from Kalundborg, could one rightfully say that the system developed is an eco-industrial park?

The companies must fit each other
The park is small and consists of only few companies, so this is hard to evaluate. However, the park as it is very symbiotic in nature. The park could be seen as a total product line to produce urea, a substance that cold be used in the area close to the production facilities. The ammonia plant is there solely to produce enough ammonia for the urea plant. However, locating the plant in the proximity of the urea plant has several advantages. Firstly, ammonia needs the input of nitrogen. As a by-product of the nitrogen pure oxygen is produced. This enables the possibility of producing electricity with carbon dioxide capture. Secondly, the ammonia requires syngas production, thus providing another source of carbon dioxide for the urea plant. These utilizations would not exist, or would be severely reduced if the companies had not been located close to each other.

The companies must be located near each other
As pointed out in the previous section, several of the exchanges would not have happened if the companies have been situated farther from each other. Also, with different industries that both produce and require heat the possibility for heat exchange is present.

There must be openness between the companies
This is hard to evaluate in an only proposed park. However, should a park of this nature be developed openness must exist. This is because the companies could not exist without the inputs from the others. Thus, the success of one company is connected to the success of others.

Seeing that the system fulfils the guidelines from Kalundborg, it could be said that system designed surely would be symbiotic of nature. The material flow analysis also show that environmental impacts in regards to emissions of carbon dioxide are reduced by 35 per cent. If the system would show economical gains for the companies involved the system could surely be called an eco-industrial park.

If the methane used in the system in time would be substituted with methane produced from either the landfill, or a process producing biogas directly from waste as the Mjøs plant.

8.6 Conclusion

It is now confirmed with high certainty that human emissions of greenhouse gasses have increased since the industrial revolution, and that these emissions have impacted the global climate of the Earth. Acknowledging that the solution to the problem is complex a paradigm change must be made when considering industrial processes if the future shall be sustainable.

The field of industrial ecology provides several tools to provide a sustainable development. One of these is eco-industrial parks, where companies located close to each other exchange resources in the form of by-products and energy. Little quantitative data could be found regarding environmental and economical benefits of the exchanges.

The development of the park at Mosseporten is based on the landfill gas produced at Solgaard Landfill. New processes have been suggested and simulated in HYSYS. The system, delivering electricity and urea shows a reduction of greenhouse gas emissions of 35 per cent compared to stand alone processes. However, the system is in need of large amounts of electric energy, and an analysis of how this is produced should be conducted to determine the real environmental gain.

The composite curves proved to be valuable tools to determine the amount of heat exchanged and the utility needed. Grand composite curve was created to determine at what level the utilities are needed. The curves combined with the energy flow sheet show that the heat demand is totally covered by the system, with the only exception of the syngas reformer. The reformer is in need of heat at a higher temperature then the system has available.

The energy flow sheets have proven to provide a good overview of the system. However, the exergy flow sheets provide a misleading image of the flows of exergy in the system. This is due to the lack of a tool in the analysis conducted to evaluate exergy losses in when heat is transferred at varying temperatures.

The CHP has an electric efficiency of 27 per cent and a total efficiency of 73,8 per cent. The electric exergy efficiency of the CHP is 28 per cent with a total system exergy efficiency of 67,7 per cent. These results show that the low electricity CHP system has better efficiencies in regards to both energy and exergy.

Based on the guidelines from Kalundborg, the system developed could be rightfully called an eco-industrial park. However, an economic evaluation must be made to conclude if the park has economic incentives for the companies involved.

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Appendix A – Gas Measurements

Daily measurements of manifold (handheld)

	Handheld	Handheld	Handheld	H Handheld
Date	CH4	H2S	CO2	O2
01.09.2005	40	378	34	1,5
05.09.2005				
06.09.2005	40	354	33	1,2
07.09.2005	40	350	33	1,3
08.09.2005	39	340	31	1,4
12.09.2005	37	282	31	1,4
13.09.2005	37	260	33	1,3
14.09.2005	51	650	37	0,7
20.09.2005	50	550	37	0,7
21.09.2005	50	550	38	0,7
22.09.2005	44	426	36	1
26.09.2005	40	350	34	1,1
27.09.2005	41	416	34	1,4
28.09.2005	40	378	34	1,3
29.09.2005	48	480	35	0,7
30.09.2005	46	450	35	0,9
	Avg CH4	Avg H2S	Avg CO2	Avg O2
	41,75	395,50	33,63	1,19

Appendix B – CHP HYSYS Data

***** Overall *****

Stream Name		**Pure oxygen from air seperation**	**23**	**24**	**25**	**Flue gas**
Vapour Fraction		1	1	0	1	1
Temperature	*C*	15	2635.523153	2635.523153	116.8943161	1400.010068
Pressure	*kPa*	4000	4000	4000	4000	4000
Flow	*kgmole/h*	8.19	12.01163595	0	3.821	42.25863595
Mass Flow	*kg/h*	262.08	323.3799212	0	61.29992123	1028.196507
Liquid Volume Flow	*m3/h*	0.230363536	0.357123384	0	0.20474665	1.120112297
Molecular Weight		32	26.9222213	26.92222433	16.04290009	24.33103872
Molar Enthalpy	*kJ/kgmole*	-637.799524	-119980.8869	-119980.9057	-71797.69144	-214772.217
Molar Entropy	*kJ/kgmole-C*	112.4782814	262.1321258	262.1321265	162.279499	218.4769761
Mass Cp	*kJ/kg-C*	0.98701456	5.170056327	5.170055193	2.634713586	2.138242444
Mass Density	*kg/m3*	54.77343838	4.436581163	4.436581662	20.09174432	6.962726376
Z Factor		0.975426625	1.003692762	1.003692762	0.984882766	1.004794123
Mole Fraction	*Methane*	0	3.76716E-13	3.76716E-13	1	1.07078E-13
	Oxygen	1	0.045622428	0.045622434	0	0.012967764
	H2O	0	0.636269363	0.636269243	0	0.751037634
	CO2	0	0.318108209	0.318108323	0	0.235994603
*****Exergy Calcs *****						
Reference State Enthalpy	*kJ/kgmole*	-300.0471584	-307851.0456	-307851.056	-75275.52237	-308514.8128
Reference State Entropy	*kJ/kgmole-C*	143.9995951	95.31170089	95.31171566	182.2527255	81.32822779
Exergy	*kJ/kgmole*	8745.114159	139800.8532	139800.8489	9233.116155	54223.18399

27	Recycled water for combustion chamber cooling	Recycled flue gas	29	30	Recycled water for turbine
1	1	1	1	1	1
339.325132	549	600	1246.868076	579.0870284	549
4000	18000	4000	4000	105	18000
3.5	3.5	26.747	50.64611531	50.64611531	8.387479362
63.05285168	63.05285168	641.7637346	1179.297791	1179.297791	151.1012835
0.063180095	0.063180095	0.699808818	1.27151851	1.27151851	0.151406212
18.01510048	18.01510048	23.99385855	23.28505915	23.28505915	18.01510048
-232198.2879	-226521.7441	-255061.1354	-217658.1404	-248030.4249	-226521.7441
166.5728141	163.3615633	187.566142	212.5911426	216.7525188	163.3615633
2.27765712	2.797294697	1.830077628	2.127032875	1.800240351	2.797294697
15.4147723	53.97318696	13.35820217	7.336431666	0.345167733	53.97318696
0.918003571	0.87892807	0.989683842	1.004562523	0.999653104	0.87892807
0	0	0	8.9345E-14	8.9345E-14	0
0	0	0	0.010820178	0.010820178	0
1	1	0.77	0.792268174	0.792268174	1
0	0	0.23	0.196911647	0.196911647	0
-287155.718	-287155.718	-311607.5494	-304978.0415	-304978.0415	-287155.718
50.56989457	50.56989457	78.91771735	76.23326227	76.23326227	50.56989457
21531.18878	28133.05457	25239.37044	48028.3779	16456.99292	28133.05457

32	33	Recycled water	36	37	1	2	3	4	Waste water
1	1	1	1	1	1	1	0.995142379	0	0
339.325132	226.1078698	549	226.1078698	226.1078698	954.3740845	600	25.38690906	25	25
4000	105	18000	105	105	4000	4000	4	101.3249966	101.3249966
8.387479362	50.64611531	11.899	26.75	23.89611531	26.75	26.75	23.89611531	18.93213165	7.033131651
151.1012835	1179.297791	214.3616806	622.8753324	556.4224586	622.8753324	622.8753324	556.4224586	341.064254	126.7025734
0.151406212	1.27151851	0.214794271	0.671583989	0.599934521	0.671583989	0.671583989	0.599934521	0.341752536	0.126958264
18.01510048	23.28505915	18.01510048	23.28505915	23.28505915	23.28505915	23.28505915	23.28505915	18.01510048	18.01510048
-232198.2879	-261987.8325	-226521.7441	-261987.8325	-261987.8325	-231683.9678	-247637.2188	-269329.5787	-286355.9268	-286355.9268
166.5728141	195.7229056	163.3615633	195.7229056	195.7229056	202.3500675	187.0420842	203.9238296	53.2984301	53.2984301
2.27765712	1.594087259	2.797294697	1.594087259	1.594087259	2.004092069	1.866789491	1.490128564	4.437055677	4.437055677
15.4147723	0.5907248	53.97318696	0.5907248	0.5907248	9.1062051	12.9748955	0.037726335	1007.336323	1007.336323
0.918003571	0.997079497	0.87892807	0.997079497	0.997079497	1.002174047	0.98882144	<empty>	0.000731	0.000731
0	8.9345E-14	0	8.9345E-14	8.9345E-14	8.9345E-14	8.9345E-14	8.9345E-14	0	0
0	0.010820178	0	0.010820178	0.010820178	0.010820178	0.010820178	0.010820178	0	0
1	0.792268174	1	0.792268174	0.792268174	0.792268174	0.792268174	0.792268174	1	1
0	0.196911647	0	0.196911647	0.196911647	0.196911647	0.196911647	0.196911647	0	0
-287155.718	-304978.0415	-287155.718	-304978.0415	-304978.0415	-304978.0415	-304978.0415	-304978.0415	-287155.718	-287155.718
50.56989457	76.23326227	50.56989457	76.23326227	76.23326227	76.23326227	76.23326227	76.23326227	50.56989457	50.56989457
21531.18878	8559.268315	28133.05457	8559.268315	8559.268315	36953.51628	25411.26066	-1145.574142	13.56371657	13.56371657

7	8	Methane from LFG	9	5	To the greenhouse	CO2 for urea prodcution
0	0	1	1	1	1	1
25	26.10035	15	25	25	25	303.7415843
101.3249966	18000	1400	101.3249966	101.3249966	101.3249966	1400
11.899	11.899	3.821	4.963983662	3.6	1.363983662	3.6
214.3616806	214.3616806	61.29992123	215.3582046	156.1829348	59.17526981	156.1829348
0.214794271	0.214794271	0.20474665	0.258181985	0.187239768	0.070942218	0.187239768
18.01510048	18.01510048	16.04290009	43.38414856	43.38414856	43.38414856	43.38414856
-286355.9268	-285929.1293	-75504.45315	-373317.0342	-373317.0342	-373317.0342	-361788.0538
53.2984301	53.29883847	159.8337964	172.663093	172.663093	172.663093	177.9558051
4.437055677	4.414672811	2.315850871	0.876234309	0.876234309	0.876234309	1.05765478
1007.336323	1011.789915	9.633039541	1.781696378	1.781696378	1.781696378	12.67839295
0.000731	0.128812333	0.97320025	0.995296392	0.995296392	0.995296392	0.998789498
0	0	1	4.30098E-13	4.30098E-13	4.30098E-13	4.30098E-13
0	0	0	0.052087244	0.052087244	0.052087244	0.052087244
1	1	0	0	0	0	0
0	0	0	0.947912756	0.947912756	0.947912756	0.947912756
-287155.718	-287155.718	-75275.52237	-373695.7234	-373695.7234	-373695.7234	-373695.7234
50.56989457	50.56989457	182.2527255	171.3712021	171.3712021	171.3712021	171.3712021
13.56371657	440.2434907	6231.083643	6.430937895	6.430937895	6.430937895	10010.31631

Appendix C – Ammonia HYSYS Data

Stream Name		**1**	**Steam**	**Natural Gas**	**Water**	**5**	**6**
Vapour Fraction		1	1	1	0	1	0
Temperature	*C*	500	500	15	15	800	800
Pressure	*kPa*	101.3249966	101.3249966	101.3249966	101.3249966	101.3249966	101.3249966
Flow	*kgmole/h*	27.5	110	27.5	110	192.4410519	0
Mass Flow	*kg/h*	441.1797523	1981.661053	441.1797523	1981.661053	2422.861935	0
Liquid Volume Flow	*m3/h*	1.473575736	1.985660127	1.473575736	1.985660127	5.180596342	0
Molecular Weight		16.04290009	18.01510048	16.04290009	18.01510048	12.59015117	12.59015117
		-	-	-		-	-
Molar Enthalpy	*kJ/kgmole*	51815.86322	224807.5761	75275.52237	-287155.718	95922.65292	95922.65289
Molar Entropy	*kJ/kgmole-C*	227.8154022	207.4398985	182.2527258	50.56989457	199.129158	199.129158
Mass Cp	*kJ/kg-C*	3.873362524	2.147075998	2.225758438	4.442605206	2.909419413	2.909419413
Mass Density	*kg/m3*	0.252794934	0.284209892	0.679842396	1014.807073	0.142964074	0.142964074
Z Factor		1.000323827	0.999133687	0.998035232	0.0007508	1.000077053	1.000077053
Mole Fraction	*Methane*	1	0	1	0	0.00015316	0.00015316
	CO	0	0	0	0	0.080508067	0.080508067
	CO2	0	0	0	0	0.062239676	0.062239676
	H2O	0	1	0	1	0.366616191	0.366616191
	Hydrogen	0	0	0	0	0.490482906	0.490482906
	Ammonia	0	0	0	0	0	0
	Nitrogen	0	0	0	0	0	0
*****Exergy Calcs *****							
		-		-		-	-
Reference State Enthalpy	*kJ/kgmole*	75275.52237	-287155.718	75275.52237	-287155.718	138412.5047	138412.5047
Reference State Entropy	*kJ/kgmole-C*	182.2527255	50.56989457	182.2527255	50.56989457	107.1748943	107.1748944
Exergy	*kJ/kgmole*	10330.77388	17146.05028	-8.06386E-05	-8.09665E-08	15993.23076	15993.23075

7	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**CO2 for urea production**
1	0	1	0	1	1	1	1	0

100	90	90	15	15	420.2932966	-35	-35	-35
101.3249966	101.3249966	101.3249966	101.3249966	101.3249966	1400	1400	1400	1400
192.4410519	70.55200544	121.8890464	70.55200544	121.8890464	121.8890464	121.8890464	109.9115777	11.9774687
2422.861935	1271.001467	1151.860468	1271.001467	1151.860468	1151.860468	1151.860468	624.7356541	527.1248135
5.180596342	1.2735664	3.907029941	1.2735664	3.907029941	3.907029941	3.907029941	3.268350133	0.638679808
12.59015117	18.01510048	9.450073665	18.01510048	9.450073665	9.450073665	9.450073665	5.683984045	44.00970078
-119752.8734	-281149.4941	-50843.65893	-287155.718	-53065.97319	-40683.43577	-54554.76168	-17315.77947	-410975.221
163.6460134	69.09314725	144.0542548	50.56989457	137.2012502	142.0166854	109.6385547	103.2115357	81.8916287
2.501218075	4.477842834	3.155736805	4.442605206	3.115690364	3.344888737	3.132639695	5.039376379	2.141042745
0.411642143	956.2255794	0.316962161	1014.807073	0.399460804	2.285372711	6.640183463	3.980477681	1095.027258
0.99888969	0.000632237	1.000533394	0.0007508	1.000534943	1.00408043	1.006249852	1.009644239	0.028416736
0.00015316	0	0.000241812	0	0.000241812	0.000241812	0.000241812	0.000268163	0
0.080508067	0	0.127107871	0	0.127107871	0.127107871	0.127107871	0.140959282	0
0.062239676	0	0.098265341	0	0.098265341	0.098265341	0.098265341	0	1
0.366616191	1	0	1	0	0	0	0	0
0.490482906	0	0.774384977	0	0.774384977	0.774384977	0.774384977	0.858772555	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
-138412.5047	-287155.718	-53065.97319	-287155.718	-53065.97319	-53065.97319	-53065.97319	-15893.14511	-394214.2254
107.1748943	50.56989457	137.2012499	50.56989457	137.2012499	137.2012499	137.2012499	130.540296	171.0791282
2387.478329	668.748644	247.6208938	-8.09665E-08	-8.08406E-05	10994.96968	6453.402146	6452.147941	8938.382373

16	17	Nitrogen Flow	19	20	21	22	23	To After Combuster
1	1	1	0	1	1	1	0	1
336.1849377	450	450	450	450	352.6079478	120	100	100
20264.99932	20264.99932	20264.99932	20264.99932	20264.99932	8000	8000	8000	8000
109.9115777	109.9115777	30.81	0	79.68441634	79.68441634	79.68441634	61.03824999	18.64616634
624.7356541	624.7356541	863.080545	0	1487.816199	1487.816199	1487.816199	1039.481439	448.3347598
3.268350133	3.268350133	1.070322853	0	2.323600163	2.323600163	2.323600163	1.687278113	0.63632205
5.683984045	5.683984045	28.01300049	18.67213706	18.67135718	18.67135718	18.67135718	17.03000069	24.04433982
-6242.920368	-2850.784578	13211.11665	-41059.92379	-41054.67666	-44875.99553	-55467.7891	-59270.98447	-89963.1381
108.1505985	113.2527666	130.4688296	160.3317611	160.3327614	162.4166435	141.1557241	102.8778254	127.3008143
5.216709527	5.268395245	1.151617024	2.652991336	2.653251478	2.414905889	2.748359915	8.335295787	1.297137862
21.31722714	18.15623317	86.90908928	61.51384624	61.51218392	28.96441271	55.28367131	469.641292	59.59718233
1.06656153	1.0551606	1.086390345	1.023087106	1.023072021	0.991215391	0.826578267	0.093503571	1.04031997
0.000268163	0.000268163	0	0.000369953	0.000369887	0.000369887	0.000369887	0	0.001580712
0.140959282	0.140959282	0	0.194519183	0.194430202	0.194430202	0.194430202	0	0.830897722
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0.858772555	0.858772555	0	0.035550409	0.035536075	0.035536075	0.035536075	0	0.151863463
0	0	0	0.765894812	0.765999838	0.765999838	0.765999838	1	0
0	0	1	0.003665643	0.003663999	0.003663999	0.003663999	0	0.015658104
-15893.14511	-15893.14511	-298.0296344	-56931.61308	-56926.58243	-56926.58243	-56926.58243	-46125.92929	-92302.57297
130.540296	130.540296	147.0694954	170.8626911	170.8629352	170.8629352	170.8629352	169.2488193	156.7756342
16101.8161	18023.76213	18292.62814	18906.17676	18906.17538	14484.38586	10018.92622	5979.746732	10832.60422

25	**Ammonia for urea production**
0	1
107.2430659	200
15000	15000
61.03824999	61.03824999
1039.481439	1039.481439
1.687278113	1.687278113
17.03000069	17.03000069
-58932.54176	-43908.46342
102.873059	138.5474792
7.177586926	4.592999282
475.6092171	90.64080052
0.169822932	0.716401707
0	0
0	0
0	0
0	0
0	0
1	1
0	0
-46125.92929	-46125.92929
169.2488193	169.2488193
6319.562878	11064.05702

Appendix D – Airsplit HYSYS Data

Stream Name		**1**	**Ambeint Air**	**Oxygen liquid**	**Nitrogen gas**	**5**	**6**
Vapour Fraction		1	1	0	1	0	0
Temperature	*C*	-185	15	-185	-185	-195.8470978	-185.7553786
Pressure	*kPa*	100	101.3249966	100	100	100	20264.99932
Flow	*kgmole/h*	39	39	8.19	30.81	30.81	30.81
Mass Flow	*kg/h*	1125.160545	1125.160545	262.08	863.080545	863.080545	863.080545
Liquid Volume Flow	*m3/h*	1.300686389	1.300686389	0.230363536	1.070322853	1.070322853	1.070322853
Molecular Weight		28.85027039	28.85027039	32	28.01300049	28.01300049	28.01300049
Molar Enthalpy	*kJ/kgmole*	-6032.035852	-298.4953518	-12927.69752	-6053.533847	-12020.57212	-11085.1837
Molar Entropy	*kJ/kgmole-C*	116.9220445	150.6978993	33.43350076	113.1394702	36.21038665	39.15638204
Mass Cp	*kJ/kg-C*	0.993052796	1.010021943	1.652885441	1.030358304	2.014280268	1.833953094
Mass Density	*kg/m3*	4.05120253	1.220505151	1155.476908	3.930372537	805.2015301	818.8596668
Z Factor		0.971665718	0.999727202	0.003778676	0.97247145	0.005412931	0.954081118
Mole Fraction	*Nitrogen*	0.79	0.79	0	1	1	1
	Oxygen	0.21	0.21	1	0	0	0
	Methane	0	0	0	0	0	0
*****Exergy Calcs *****							
Reference State Enthalpy	*kJ/kgmole*	-298.495352	-298.495352	-300.0471584	-298.0296344	-298.0296344	-298.0296344
Reference State Entropy	*kJ/kgmole-C*	150.697899	150.697899	143.9995951	147.0694954	147.0694954	147.0694954
Exergy	*kJ/kgmole*	3998.971971	-8.07753E-05	19231.96971	4021.43255	20221.50972	20308.00956

7	**Oxygen for combustion**	**Nitrogen for ammonia production**
0	1	1
-183.4886224	15	450
4000	4000	20264.99932
8.19	8.19	30.81
262.08	262.08	863.080545
0.230363536	0.230363536	1.070322853
32	32	28.01300049
-12783.68772	-637.799524	13211.11665
33.84228153	112.4782814	130.4688296
1.632435433	0.98701456	1.151617024
1157.08058	54.77343838	86.90908928
0.148393276	0.975426625	1.086390345
0	0	1
1	1	0
0	0	0
-300.0471584	-300.0471584	-298.0296344
143.9995951	143.9995951	147.0694954
19258.18933	8745.114159	18292.62814

Appendix E – Utility and LFG HYSYS Data

Stream Name		**1**	**Combustion Air**	**3**	**4**	**Emissions**
Vapour Fraction		1	1	1	0	1
Temperature	*C*	95.41013409	15	1652.279539	1652.279539	100
Pressure	*kPa*	101.3	101.3	101.3	101.3	101.3
Flow	*kgmole/h*	18.64	75	84.49983637	0	84.49983637
Mass Flow	*kg/h*	448.1865165	2163.770279	2611.935627	0	2611.935627
Liquid Volume Flow	*m3/h*	0.636095941	2.501319978	3.131655197	0	3.131655197
Molecular Weight		24.04434101	28.85027039	30.91054065	30.91054065	30.91054065
Molar Enthalpy	*kJ/kgmole*	-89973.37596	-298.4935349	-20112.35732	-20112.35732	-78107.95789
Molar Entropy	*kJ/kgmole-C*	163.9319498	150.6999564	226.713323	226.713323	167.4856065
Mass Cp	*kJ/kg-C*	1.214211963	1.010021439	1.328109923	1.328109923	1.028645041
Mass Density	*kg/m3*	0.794495859	1.220203975	0.195568123	0.195568123	1.009488811
Z Factor		1.000450471	0.999727269	1.000146483	<empty>	0.999779795
Mole Fraction	*Methane*	0.001540002	0	7.75809E-24	7.75809E-24	7.75809E-24
	H2O	0	0	0.034162979	0.034162979	0.034162979
	CO2	0	0	0.183191811	0.183191811	0.183191811
	CO	0.831017831	0	0.000463906	0.000463906	0.000463906
	Oxygen	0	0.21	0.077543643	0.077543643	0.077543643
	Nitrogen	0.015560016	0.79	0.704617207	0.704617207	0.704617207
	Hydrogen	0.151882152	0	2.04552E-05	2.04552E-05	2.04552E-05
*****Exergy Calcs *****						
Reference State Enthalpy	*kJ/kgmole*	-92312.80333	-298.495352	-81580.12194	-81580.12194	-81580.12194
Reference State Entropy	*kJ/kgmole-C*	156.7699565	150.697899	156.6446462	156.6446462	156.6446462
Exergy	*kJ/kgmole*	275.6989886	-0.591022292	41277.47543	41277.47543	348.3413535

Remains of ammonia prodcution	Methane flow	Air to combustion	Emmision	10	11	12	13
1	1	1	1	0	0	0.678825311	0.924126117
100	15	15	100	100	130	130	130
8000	101.3	101.3	101.3	101.3	269.9426018	269.9421289	269.9424078
18.64	2.880244408	57.60488817	60.48513257	0	125.6	125.6	125.6
448.1865165	46.20747326	1661.916599	1708.115436	0	2262.69662	2262.69662	2262.69662
0.636095941	0.154336665	1.921176768	2.016718846	0	2.267262835	2.267262835	2.267262835
24.04434101	16.04290009	28.85027039	28.24025283	28.24025283	18.01510048	18.01510048	18.01510048
-89973.37596	-75275.518	-298.4935349	-39520.58652	-39520.58652	-277888.835	-251095.2044	-241413.0388
127.295086	182.2547883	150.6999564	164.9461484	164.9461484	77.59815622	144.0588643	168.0751458
1.29711579	2.225756804	1.010021439	1.083175943	1.083175943	4.575114551	2.787180083	2.141090822
59.5970581	0.679674351	1.220203975	0.922376703	0.922376703	921.9337933	2.175203124	1.598818383
1.04032219	0.998035717	0.999727269	0.999676583	<empty>	0.001573675	<empty>	<empty>
0.001540002	1	0	1.67165E-39	1.67165E-39	0	0	0
0	0	0	0.095238095	0.095238095	1	1	1
0	0	0	0.047619048	0.047619048	0	0	0
0.831017831	0	0	1.52391E-36	1.52391E-36	0	0	0
0	0	0.21	0.104761905	0.104761905	0	0	0
0.015560016	0	0.79	0.752380952	0.752380952	0	0	0
0.151882152	0	0	1.1649E-32	1.1649E-32	0	0	0
-92312.80333	-75275.52237	-298.495352	-45692.34096	-45692.34096	-287155.718	-287155.718	-287155.718
156.7699565	182.2527255	150.697899	145.3951438	145.3951438	50.56989457	50.56989457	50.56989457
10832.61129	-0.590022151	-0.591022292	538.1324622	538.1324622	1478.689439	9121.666967	11883.54107

14	LFG	5	Cooled LFG	LFG Methane	CO2 for Urea	2	CO2 from syngas	7
1	1	1	1	1	0	0	0	0
130	15	283.3600572	-35	-35	-35	-35	-35	-35.00821547
269.9426001	101.3249966	1400	1400	1400	1184.134763	1400	1400	1184.134763
125.6	9.553	9.553	9.553	3.8212	5.7318	3.42	11.98	21.1318
2262.69662	313.5579327	313.5579327	313.5579327	61.30312981	252.2548029	150.5131767	527.2362153	930.0041948
2.267262835	0.510396649	0.510396649	0.510396649	0.204757367	0.305639281	0.182366158	0.638814786	1.126820225
18.01510048	32.8229805	32.8229805	32.8229805	16.04290009	44.00970078	44.00970078	44.00970078	44.00970078
-238418.2525	-266636.096	-255445.9889	-269036.0992	-77343.61037	-410974.1562	-410975.221	-410975.221	-410974.9322
175.5036068	181.1502305	186.4670399	150.7117939	152.8252404	81.93595344	81.8916287	81.8916287	81.93268491
1.941249259	1.132966743	1.453079485	1.231031428	2.283507382	2.146434649	2.141042745	2.141042745	2.146325275
1.477705334	1.393439553	9.931386643	25.85527079	11.98123198	1094.174379	1095.027258	1095.027258	1094.208376
0.981808697	0.996233448	0.999991728	0.897593375	0.946743029	0.02405391	0.028416736	0.028416736	0.024053993
0	0.4	0.4	0.4	1	0	0	0	0
1	0	0	0	0	0	0	0	0
0	0.6	0.6	0.6	0	1	1	1	1
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
-287155.718	-266636.096	-266636.096	-266636.096	-75275.52237	-394214.2254	-394214.2254	-394214.2254	-394214.2254
50.56989457	181.1502302	181.1502302	181.1502302	182.2527255	171.0791282	171.0791282	171.0791282	171.0791282
12737.81626	-8.04931E-05	9658.06841	6370.832265	6411.441835	8926.675085	8938.382373	8938.382373	8926.840868

8	Total CO2 for Urea Production	Oxygen	16	From CHP
0	1	1	0.328593289	1
-26.79218951	200	-35	-35	303.7
15000	15000	1400	1400	1400
21.1318	21.1318	0.18	3.6	3.6
930.0041948	930.0041948	5.76	156.2731767	156.2731767
1.126820225	1.126820225	0.005062935	0.187429092	0.187429092
44.00970078	44.00970078	32	43.40921574	43.40921574
-410234.0226	-389044.1328	-1908.137031	-386531.2789	-362605.4135
82.51211355	145.4303265	116.1498892	101.2299032	177.9744705
1.968317551	1.297845564	0.934589865	1.778440995	1.057737199
1113.486892	181.8643046	23.14506929	100.7597801	12.68687618
0.289441963	0.922712977	0.977557264	<empty>	0.998770351
0	0	0	0	0
0	0	0	0	0
1	1	0	0.95	0.95
0	0	0	0	0
0	0	1	0.05	0.05
0	0	0	0	0
0	0	0	0	0
-394214.2254	-394214.2254	-300.0471584	-374517.9412	-374517.9412
171.0791282	171.0791282	143.9995951	171.3769518	171.3769518
9500.788077	12560.79488	6416.802884	8199.534376	10011.45269

Appendix F – HYSYS State Data

Stream Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Vapour Fraction		0	0	1	1	1	1	1
Temperature	*C*	-185	-183.5	15	25.4	100	226.0182648	305.3889751
Pressure	*kPa*	100	4000	4000	4	101.3249966	105	1400
Flow	*kgmole/h*	1	1	1	1	1	1	1
Mass Flow	*kg/h*	32	32	32	32	32	32	32
Liquid Volume Flow	*m3/h*	0.028127416	0.028127416	0.028127416	0.028127416	0.028127416	0.028127416	0.028127416
Molecular Weight		32	32	32	32	32	32	32
Molar Enthalpy	*kJ/kgmole*	-12927.69752	-12784.28205	-637.799524	11.33793842	2210.807764	6062.062768	8552.479805
Molar Entropy	*kJ/kgmole-C*	33.43350076	33.83565279	112.4782814	171.9283021	151.6308852	160.2182899	143.2807484
Mass Cp	*kJ/kg-C*	1.652885441	1.632383128	0.98701456	0.911561303	0.936127604	0.973654271	1.000658808
Mass Density	*kg/m3*	1155.476908	1157.134271	54.77343838	0.051567497	1.045137088	0.809383883	9.275503612
Z Factor		0.003778676	0.148405222	0.975426625	0.999977221	0.999961168	1.000255672	1.004109689
Mole Fraction	*Methane*	0	0	0	0	0	0	0
	Oxygen	1	1	1	1	1	1	1
	Nitrogen	0	0	0	0	0	0	0
	CO2	0	0	0	0	0	0	0
	Hydrogen	0	0	0	0	0	0	0
	CO	0	0	0	0	0	0	0
	Ammonia	0	0	0	0	0	0	0
	H2O	0	0	0	0	0	0	0

8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	1	1	1	1	1	0	0	1	1
578.9603636	600	954.2067708	1246.684578	1400	1652.279539	-195.8470978	-185.7553786	-185	15
105	4000	4000	4000	4000	101.3249966	100	20264.99932	100	101.3249966
1	1	1	1	1	1	1	1	1	1
32	32	32	32	32	32	28.01300049	28.01300049	28.01300049	28.01300049
0.028127416	0.028127416	0.028127416	0.028127416	0.028127416	0.028127416	0.034739463	0.034739463	0.034739463	0.034739463
32	32	32	32	32	32	28.01300049	28.01300049	28.01300049	28.01300049
17587.24545	18349.97089	30816.53875	41412.75347	46992.31871	56010.47602	-12020.57212	-11085.18371	-6053.533847	-298.0296341
177.6130702	148.1413982	160.1100555	167.851757	171.349381	206.9782189	36.21038665	39.15638584	113.1394702	147.0694957
1.062547285	1.071618241	1.122516911	1.137641047	1.135838272	1.1197463	2.014280268	1.833953108	1.030358304	1.040362209
0.474119584	17.43677016	12.43668722	10.05985209	9.144292102	0.202513451	805.2015301	818.8596452	3.930372537	1.184944765
1.000296616	1.011179678	1.00857384	1.006920813	1.006232327	1.000134333	0.005412931	0.954081144	0.97247145	0.999845188
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
1	1	1	1	1	1	1	0	1	1
95	100	100	120	353	450	1652.279539	-35	15	25.38626395
101.3249966	8000	101.3249966	8000	8000	20264.99932	101.3249966	1400	101.3249966	4
1	1	1	1	1	1	1	1	1	1
28.01300049	28.01300049	28.01300049	28.01300049	28.01300049	28.01300049	28.01300049	44.00970078	44.00970078	44.00970078
0.034739463	0.034739463	0.034739463	0.034739463	0.034739463	0.034739463	0.034739463	0.053323438	0.053323438	0.053323438
28.01300049	28.01300049	28.01300049	28.01300049	28.01300049	28.01300049	28.01300049	44.00970078	44.00970078	44.00970078
2049.28467	1983.936225	2197.056289	2617.721608	9924.49737	13211.11665	53459.00778	-410975.221	-394214.2254	-393776.8132
154.2564279	117.5216387	154.6551159	119.1761965	133.7731016	130.4688296	207.454133	81.8916287	171.0791285	199.4004224
1.054570957	1.134354585	1.055472605	1.128412166	1.122543125	1.151617024	1.275661666	2.141042745	0.867969793	0.870066232
0.927021665	69.9793881	0.914586754	66.25390603	41.51571275	86.90908928	0.177278329	1095.027258	1.871807953	0.070936535
1.000310442	1.032212927	1.000325035	1.03479212	1.036888355	1.086390345	1.00015247	0.028416736	0.994393704	0.999803397
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

28	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**
1	1	1	1	1	1	1	1	1	1
90	100	226.0182648	284.9	305.3889751	423	578.9603636	600	800	954.2067708
101.3249966	101.3249966	105	1400	1400	1400	105	4000	101.3249966	4000
1	1	1	1	1	1	1	1	1	1
44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078
0.053323438	0.053323438	0.053323438	0.053323438	0.053323438	0.053323438	0.053323438	0.053323438	0.053323438	0.053323438
44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078	44.00970078
-391265.2176	-390859.534	-385510.0327	-383013.1893	-382060.8838	-376429.2917	-368531.9344	-367508.89	-356751.9424	-348077.9936
180.1653142	181.2673161	193.2987537	176.5254328	178.2012935	187.0558093	218.8460943	189.6738535	231.4193848	208.3118334
0.918527706	0.925073301	1.002773688	1.051256081	1.060944157	1.114352819	1.171973493	1.19431815	1.246341289	1.291860755
1.480614327	1.440575591	1.114059544	13.3153332	12.82919111	10.62081313	0.652058573	23.96737586	0.499626035	17.05737879
0.997493977	0.997743208	0.999437427	0.99729712	0.998430454	1.00228013	1.000295978	1.011747935	1.0003058	1.011343191
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

38	39	40	41	42	43	44	45	46	47
1	1	1	1	1	1	1	1	1	1
1246.684578	1400	1652.279539	-35	15	284.9	405.7881348	500	-35	15
4000	4000	101.3249966	1400	101.3249966	1400	4000	101.3249966	1400	101.3249966
1	1	1	1	1	1	1	1	1	1
44.00970078	44.00970078	44.00970078	16.04290009	16.04290009	16.04290009	16.04290009	16.04290009	2.016000032	2.016000032
0.053323438	0.053323438	0.053323438	0.053584572	0.053584572	0.053584572	0.053584572	0.053584572	0.028858088	0.028858088
44.00970078	44.00970078	44.00970078	16.04290009	16.04290009	16.04290009	16.04290009	16.04290009	2.016000032	2.016000032
-	-	-	-	-	-	-	-	-	-
331090.9677	321958.6765	306859.7649	77343.61037	75275.52237	63938.49893	57495.06454	51815.86322	1690.473361	282.9460023
220.7170246	226.4410149	265.4683282	152.8252404	182.2527258	187.6842801	189.3253925	227.8154022	94.76517169	122.037627
1.343672383	1.362403351	1.382584885	2.283507382	2.225758438	3.12215054	3.584754938	3.873362524	14.10648083	14.09079121
13.80145843	12.54899157	0.278505561	11.98123198	0.679842396	4.827763998	11.23090518	0.252794934	1.410906626	0.085207924
1.009393186	1.00841191	1.000176799	0.946743029	0.998035232	1.002686193	1.012211276	1.000323827	1.010282839	1.000649051
0	0	0	1	1	1	1	1	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

48	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**
1	1	1	1	1	1	1	1	1	1
90	95	100	100	120	336	353	423	450	800
101.3249966	101.3249966	101.3249966	8000	8000	20264.99932	800	1400	20264.99932	101.3249966
1	1	1	1	1	1	1	1	1	1
2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032
0.028858088	0.028858088	0.028858088	0.028858088	0.028858088	0.028858088	0.028858088	0.028858088	0.028858088	0.028858088
2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032	2.016000032
1853.888357	1996.811371	2139.794922	2258.903371	2835.102379	9317.150255	9473.223123	11541.92304	12673.71243	22871.64973
128.627891	129.0187725	129.4045442	93.06594194	94.57059901	99.5915143	127.1906685	125.6561114	104.6429221	160.4963563
14.17598208	14.18196669	14.18798652	14.29373434	14.30205735	14.5409966	14.53171196	14.63661112	14.68280383	15.24747186
0.067618394	0.066700505	0.065807206	4.995345036	4.750670871	7.606191883	0.309085444	0.485909615	6.475481074	0.022890547
1.000528575	1.000521605	1.000514765	1.040650385	1.038581453	1.060520009	1.002297963	1.003537289	1.049324864	1.000146915
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

58	59	60	61	62	63	64	65	66	67
1	1	1	1	1	1	1	1	1	1
-35	15	90	95	100	100	336	120	353	423
1400	101.3249966	101.3249966	101.3249966	101.3249966	8000	20264.99932	8000	8000	1400
1	1	1	1	1	1	1	1	1	1
28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005
0.035040432	0.035040432	0.035040432	0.035040432	0.035040432	0.035040432	0.035040432	0.035040432	0.035040432	0.035040432
28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005	28.0109005
-112493.4237	-110888.1944	-108699.6877	-108553.3169	-108406.8692	-108630.651	-101088.0167	-107997.2235	-100735.1576	-98658.14424
130.193411	158.0994417	164.8491592	165.2494683	165.6445845	128.4539607	135.8104058	130.1076014	144.6167881	162.5129318
1.088677834	1.039589256	1.044831425	1.04536992	1.045929409	1.135201611	1.146685324	1.126561302	1.11726835	1.114138538
20.06488855	1.184849848	0.939689257	0.926911536	0.914477387	69.74280384	101.6798421	66.02400486	41.4190615	6.732252855
0.987054274	0.999850325	1.000337669	1.000354295	1.00036967	1.035636798	1.102269567	1.03831751	1.039230019	1.006387246
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

68	**69**	**70**	**71**	**72**	**73**	**74**	**75**	**76**	**77**
1	1	1	0	0	1	1	1	1	0
450	800	15	100	107	120	200	353	450	15
20264.99932	101.3249966	101.3249966	8000	15000	8000	15000	8000	20264.99932	101.3249966
1	1	1	1	1	1	1	1	1	1
28.0109005	28.0109005	17.03000069	17.03000069	17.03000069	17.03000069	17.03000069	17.03000069	17.03000069	18.01510048
0.035040432	0.035040432	0.027642963	0.027642963	0.027642963	0.027642963	0.027642963	0.027642963	0.027642963	0.018051456
28.0109005	28.0109005	17.03000069	17.03000069	17.03000069	17.03000069	17.03000069	17.03000069	17.03000069	18.01510048
-	-	-	-	-	-	-	-	-	
97418.18852	86456.78982	46125.92929	59270.98447	58962.21776	46376.01919	43908.46342	33650.75005	29877.22547	-287155.718
141.3324094	198.3551599	169.2488196	102.8778254	102.7950181	136.3741994	138.5474792	162.2029559	160.3006725	50.56989457
1.154046021	1.200567404	2.10143004	8.335295787	7.160713079	5.308541057	4.592999282	2.940230752	3.300449579	4.442605206
86.58050642	0.317997258	0.726647042	469.641292	476.2098592	65.35102141	90.64080052	27.14259249	58.32209979	1014.807073
1.09043157	1.000306585	0.991202511	0.093503571	0.169717182	0.637774656	0.716401707	0.964157992	0.984176478	0.0007508
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0	0
0	0	1	1	1	1	1	1	1	0
0	0	0	0	0	0	0	0	0	1

78	79	80	81	82	83	84	85	86	87
0	1	0	0	1	1	1	1	1	1
25	29.34417114	26.04	90	100	226.0182648	339.325132	549	578.9603636	600
101.3249966	4	18000	101.3249966	101.373483	105	4000	18000	105	4000
1	1	1	1	1	1	1	1	1	1
18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048
0.018051456	0.018051456	0.018051456	0.018051456	0.018051456	0.018051456	0.018051456	0.018051456	0.018051456	0.018051456
18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	18.01510048
-286355.9268	-241671.7318	-285933.929	-281149.4941	-239347.2052	-234954.7969	-232198.2879	-226521.7441	-221716.5499	-221536.198
53.2984301	201.0340112	53.28279859	69.09314725	181.148104	190.9913295	166.5728142	163.3615633	210.9498785	181.0709308
4.437055677	1.86605672	4.414707178	4.477842834	1.907334126	1.968404402	2.277657119	2.797294697	2.199620722	2.300913991
1007.336323	0.028668114	1011.834218	956.2255794	0.593598212	0.457521875	15.41477227	53.97318696	0.26715699	10.13556425
0.000731	0.999433303	0.128832674	0.000632237	0.991649714	0.996185972	0.918003573	0.87892807	0.999394288	0.979339238
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1

88	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**
1	1	1	1	1	1	1	1	1	1
800	954.2	1246	1400	1652.3	15	500	25	25	15
101.3249966	4000	4000	4000	101.3249966	101.3249966	101.3249966	100	100	1400
1	1	1	1	1	1	1	1	1	1
18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	32	18.01510048	32	44.00970078	16.04290009
0.018051456	0.018051456	0.018051456	0.018051456	0.018051456	0.028127416	0.018051456	0.028127416	0.053323438	0.053584572
18.01510048	18.01510048	18.01510048	18.01510048	18.01510048	32	18.01510048	32	44.00970078	16.04290009
-	-	-	-	-	-	-	-	-	-
212681.4095	206367.4314	193044.9281	185590.1134	172231.1184	300.0471581	224807.5761	8.227365007	393830.1887	75504.45315
220.6626409	195.6258948	205.3529523	210.0251758	248.0436745	143.9995953	207.4398985	145.1045164	172.498126	159.8337964
2.335007335	2.457572042	2.623220772	2.75978867	3.137156856	0.91006305	2.147075998	0.913107359	0.874763294	2.315850871
0.204616486	7.072261234	5.690126538	5.161882999	0.114011672	1.354333347	0.284209892	1.291626709	1.784195354	9.633039541
0.999828469	0.998488859	1.002645392	1.003522029	1.000103603	0.999299441	0.999133687	0.999427769	0.995048988	0.97320025
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	1	0	1	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	0	1	0	0	0

98	99	100
1	0	1
116.9	-26	200
4000	15000	15000
1	1	1
16.04290009	44.00970078	44.00970078
0.053584572	0.053323438	0.053323438
16.04290009	44.00970078	44.00970078
-	-	-
71797.45119	410165.3126	389044.1328
162.2801149	82.79056719	145.4303265
2.634726826	1.973294188	1.297845564
20.09141753	1110.861233	181.8643046
0.984884433	0.289196154	0.922712977
1	0	0
0	0	0
0	0	0
0	1	1
0	0	0
0	0	0
0	0	0
0	0	0

Appendix G – Energy Calculations

		Prosess	T	P	xO2	xN2	xCO2	xCH4	xH2	xCO	xNH3	xH2O	xtot	Flow	h	hhv	Energy	
Natural Gas		Syngas	15	1.013				1.0					1	28	0	6801	6801	kW
Water		Syngas	15	1.013								1.0	1	110	0	0	0	kW
	1	Syngas	500	1.013				1.0					1	28	179	6801	6980	kW
Steam		Syngas	500	1.013								1.0	1	110	1905	0	1905	kW
	5	Syngas	800	1.013			0.1		0.5	0.1		0.4	1	192	2296	8712	11009	kW
	7	Syngas	100	1.013			0.1		0.5	0.1		0.4	1	192	1022	8712	9735	kW
	8	Syngas	90	1.013								1.0	1	71	118	0	118	kW
	9	Syngas	90	1.013			0.1		0.8	0.1			1	122	75	8712	8788	kW
	10	Syngas	15	1.013								1.0	1	71	0	0	0	kW
	11	Syngas	15	1.013			0.1		0.8	0.1			1	122	0	8712	8712	kW
	12	Syngas	423	14.000			0.1		0.8	0.1			1	122	422	8712	9134	kW
	13	Syngas	-35	14.000			0.1		0.8	0.1			1	122	-100	8712	8613	kW
CO2 for urea		Syngas	-35	14.000			1.0						1	12	-56	0	-56	kW
	14	Syngas	-35	14.000					0.9	0.1			1	110	-44	8712	8669	kW
	16	Syngas	336	202.650					0.9	0.1			1	110	294	8712	9006	kW
	17	Synga	450	202.65					0.9	0.1			1	110	398	871	9110	kW

		s		0												2		
Nitrogen flow		Syngas	450	202.650		1.0							1	31	116	0	116	kW
	20	Syngas	450	202.650					0.0	0.2	0.8		1	80	344	7932	8275	kW
	21	Syngas	353	80.000					0.0	0.2	0.8		1	80	263	7932	8195	kW
	22	Syngas	120	80.000					0.0	0.2	0.8		1	80	11	7932	7942	kW
To after combuster		Syngas	100	80.000		0.0			0.2	0.8			1	19	12	1404	1416	kW
	23	Syngas	100	80.000							1.0		1	61	-223	6489	6266	kW
	25	Syngas	107	150.000							1.0		1	61	-218	6489	6271	kW
Ammonia for urea		Syngas	200	150.000							1.0		1	61	38	6489	6527	kW
Pure oxygen		CHP	15	40.000	1.0								1	8	0	0	0	kW
LFG Methane		CHP	15	14.000				1.0					1	4	0	945	945	kW
	25	CHP	117	40.000				1.0					1	4	4	945	949	kW
Flue Gas		CHP	1400	40.000	0.0		0.2					0.8	1	42	1103	0	1103	kW
	29	CHP	1247	40.000	0.0		0.2					0.8	1	51	1230	0	1230	kW
	30	CHP	579	1.050	0.0		0.2					0.8	1	51	803	0	803	kW
	33	CHP	226	1.050	0.0		0.2					0.8	1	51	607	0	607	kW
	36	CHP	226	1.050	0.0		0.2					0.8	1	27	321	0	321	kW
Same com flow		CHP	954	40.000	0.0		0.2					0.8	1	27	546	0	546	kW
into mix 101		CHP	600	40.000	0.0		0.2					0.8	1	27	427	0	427	kW

	3	CHP	25	0.040	0.0		0.2		0.8	1	24	240	0	240	kW
	9	CHP	25	1.000	0.1		0.9			1	5	1	0	1	kW
CO2 for the greenhouse		CHP	25	1.000	0.1		0.9			1	1	0	0	0	kW
CO2 for urea		CHP	305	14.000	0.1		0.9			1	4	12	0	12	kW
	4	CHP	25	1.013					1.0	1	19	4	0	4	kW
Waste Water		CHP	25	1.013					1.0	1	7	2	0	2	kW
	7	CHP	25	1.013					1.0	1	12	3	0	3	kW
	8	CHP	26	180.000					1.0	1	12	4	0	4	kW
Recycled water		CHP	549	180.000					1.0	1	12	200	0	200	kW
RW for cc		CHP	549	180.000					1.0	1	4	59	0	59	kW
	27	CHP	339	40.000					1.0	1	4	53	0	53	kW
RW for turbine		CHP	549	180.000					1.0	1	8	141	0	141	kW
	32	CHP	339	40.000					1.0	1	8	128	0	128	kW
Ambient air		Airsplit	15	1.000	0.2	0.8				1	39	0	0	0	kW
1 inkl splitter		Airsplit	-185	1.000	0.2	0.8				1	39	-78	0	-78	kW
Oxygen liquid		Airsplit	-185	1.000	1.0					1	8	-29	0	-29	kW
Nitrogen gas		Airsplit	-185	1.000		1.0				1	31	-49	0	-49	kW
	7	Airsplit	-183	40.000	1.0					1	8	-28	0	-28	kW
Oxygen for comb		Airsplit	15	40.000	1.0					1	8	-1	0	-1	kW
	5	Airsplit	-196	1.000		1.0				1	31	-100	0	-100	kW
	6	Airsplit	-186	202.650		1.0				1	31	-92	0	-92	kW
Nitrogen for amm		Airsplit	450	202.650		1.0				1	31	116	0	116	kW
LFG		LFG	15	1.000			0.6	0.4		1	10	0	945	945	kW
Comp LFG		LFG	285	14.000			0.6	0.4		1	10	30	945	975	kW
Cool LFG		LFG	-35	14.000			0.6	0.4		1	10	-29	945	916	kW
CO2 LFG		LFG	-35	14.000			1.0			1	6	-27	0	-27	kW
CH4 LFG		LFG	-35	14.000				1.0		1	4	-2	945	943	kW

Remains of ammonia prodcution	Utility	100	80.000		0.0			0.2	0.8		1	19	12	1442	1454	kW
1	Utility	95	1.013		0.0			0.2	0.8		1	19	12	1442	1454	kW
Combustion Air	Utility	15	1.013	0.2	0.8						1	75	0	0	0	kW
3	Utility	1652	1.013	0.1	0.7	0.2				0.0	1	84	1459	0	1459	kW
Emissions	Utility	100	1.013	0.1	0.7	0.2				0.0	1	84	99	0	99	kW
Methane flow	Utility	15	1.013				1.0				1	3	0	712	712	kW
Air to combustion	Utility	15	1.013	0.2	0.8						1	58	0	0	0	kW
Emission	Utility	100	1.013	0.1	0.8	0.0				0.1	1	60	115	0	115	kW
From CHP	CO2	304	14.000	0.1		1.0					1	4	12	0	12	kW
Oxygen	CO2	-35	14.000	1.0							1	0	0	0	0	kW
2	CO2	-35	14.000			1.0					1	3	-16	0	-16	kW
7	CO2	-35	14.000			1.0					1	21	-98	0	-98	kW
8	CO2	-27	150.000			1.0					1	21	-94	0	-94	kW
Total CO2 for Urea Production	CO2	200	150.000			1.0					1	21	30	0	30	kW

Appendix H – Exergy Calculations

		Prosess	T	P	xO2	xN2	xCO2	xCH4	xH2	xCO	xNH3	xH2O	xtot	Flow	atm-flow	atm	ach	atot	
Natural Gas		Syngas	15	1.013				1.0					1.0	27.50	0	0	6353	6353	kW
Water		Syngas	15	1.013								1.0	1.0	110.00	0	0	28	28	kW
	1	Syngas	500	1.013				1.0					1.0	27.50	10331	79	6353	6432	kW
Steam		Syngas	500	1.013								1.0	1.0	110.00	17146	524	290	814	kW
	5	Syngas	800	1.013			0.1		0.5	0.1		0.4	1.0	192.44	15993	855	7487	8342	kW
	7	Syngas	100	1.013			0.1		0.5	0.1		0.4	1.0	192.44	2387	128	7487	7615	kW
	8	Syngas	90	1.013								1.0	1.0	70.55	669	13	18	31	kW
	9	Syngas	90	1.013			0.1		0.8	0.1			1.0	121.89	248	8	7385	7393	kW
	10	Syngas	15	1.013								1.0	1.0	70.55	0	0	18	18	kW
	11	Syngas	15	1.013			0.1		0.8	0.1			1.0	121.89	0	0	7385	7385	kW
	12	Syngas	423	14.000			0.1		0.8	0.1			1.0	121.89	10995	372	7385	7757	kW
	13	Syngas	-35	14.000			0.1		0.8	0.1			1.0	121.89	6453	219	7385	7603	kW
CO2 for urea		Syngas	-35	14.000			1.0						1.0	11.98	8938	30	66	96	kW
	14	Syngas	-35	14.000					0.9	0.1			1.0	109.91	6452	197	7345	7542	kW
	16	Syngas	336	202.650					0.9	0.1			1.0	109.91	16102	492	7345	7836	kW
	17	Syngas	450	202.650					0.9	0.1			1.0	109.91	18024	550	7345	7895	kW

Nitrogen flow	Syngas	450	202.650		1.0							1.0	30.81	18293	157	6	163	kW
20	Syngas	450	202.650					0.0	0.2	0.8		1.0	79.69	18906	418	7065	7483	kW
21	Syngas	353	80.000					0.0	0.2	0.8		1.0	79.69	14484	321	7065	7386	kW
22	Syngas	120	80.000					0.0	0.2	0.8		1.0	79.69	10019	222	7065	7287	kW
To after combuster	Syngas	100	80.000		0.0			0.2	0.8			1.0	18.65	10833	56	1363	1420	kW
23	Syngas	100	80.000							1.0		1.0	61.04	5980	101	5729	5831	kW
25	Syngas	107	150.000							1.0		1.0	61.04	6320	107	5729	5836	kW
Ammonia for urea	Syngas	200	150.000							1.0		1.0	61.04	11064	188	5729	5917	kW
																	0	kW
Pure oxygen	CHP	15	40.000	1.0								1.0	8.19	8745	20	9	29	kW
LFG Methane	CHP	15	14.000				1.0					1.0	3.82	6231	7	883	889	kW
25	CHP	117	40.000				1.0					1.0	3.82	9233	10	883	893	kW
Flue Gas	CHP	1400	40.000	0.0		0.2					0.8	1.0	42.26	54217	636	122	759	kW
29	CHP	1247	40.000	0.0		0.2					0.8	1.0	50.66	48022	676	143	819	kW
30	CHP	579	1.050	0.0		0.2					0.8	1.0	50.66	16454	232	143	374	kW
33	CHP	226	1.050	0.0		0.2					0.8	1.0	50.66	8558	120	143	263	kW
36	CHP	226	1.050	0.0		0.2					0.8	1.0	26.75	8558	64	75	139	kW
Same com flow	CHP	954	40.000	0.0		0.2					0.8	1.0	26.75	36946	275	75	350	kW
into mix 101	CHP	600	40.000	0.0		0.2					0.8	1.0	26.75	25411	189	75	264	kW

	37	CHP	226	1.050	0.0		0.2		0.8	1.0	23.91	8558	57	67	124	kW
	3	CHP	25	0.040	0.0		0.2		0.8	1.0	23.91	-1146	-8	67	60	kW
	9	CHP	25	1.000	0.1		0.9			1.0	4.97	6	0	26	26	kW
CO2 for urea		CHP	305	14.000	0.1		0.9			1.0	3.6	10010	10	19	29	kW
CO2 for the greenhouse		CHP	25	1.000	0.1		0.9			1.0	1.364	6	0	7	7	kW
	4	CHP	25	1.013					1.0	1.0	18.94	14	0	5	5	kW
Waste Water		CHP	25	1.013					1.0	1.0	7.04	14	0	2	2	kW
	7	CHP	25	1.013					1.0	1.0	11.90	14	0	3	3	kW
	8	CHP	26	180.000					1.0	1.0	11.90	440	1	3	4	kW
Recycled water		CHP	549	180.000					1.0	1.0	11.90	28133	93	31	124	kW
RW for cc		CHP	549	180.000					1.0	1.0	3.50	28133	27	9	37	kW
	27	CHP	339	40.000					1.0	1.0	3.50	21531	21	9	30	kW
RW for turbine		CHP	549	180.000					1.0	1.0	8.40	28133	66	22	88	kW
	32	CHP	339	40.000					1.0	1.0	8.40	21531	50	22	72	kW
															0	kW
Ambient air		Airsplit	15	1.000	0.2	0.8				1.0	39.00	0	0	0	0	kW
1 inkl splitter		Airsplit	-185	1.000	0.2	0.8				1.0	39.00	3999	43	0	43	kW
Oxygen liquid		Airsplit	-185	1.000	1.0					1.0	8.19	19232	44	9	53	kW
Nitrogen gas		Airsplit	-185	1.000		1.0				1.0	30.81	4021	34	6	41	kW
	7	Airsplit	-183	40.000	1.0					1.0	8.19	19258	44	9	53	kW
Oxygen for comb		Airsplit	15	40.000	1.0					1.0	8.19	8745	20	9	29	kW
	5	Airsplit	-196	1.000		1.0				1.0	30.81	20222	173	6	179	kW
	6	Airsplit	-186	202.650		1.0				1.0	30.81	20308	174	6	180	kW
Nitrogen for amm		Airsplit	450	202.650		1.0				1.0	30.81	18293	157	6	163	kW
															0	kW
LFG		LFG	15	1.000			0.6	0.4		1.0	9.55	0	0	910	910	kW
Comp LFG		LFG	285	14.000			0.6	0.4		1.0	9.55	9658	26	910	936	kW
Cool LFG		LFG	-35	14.000			0.6	0.4		1.0	9.55	6371	17	910	927	kW
CO2 LFG		LFG	-35	14.000			1.0			1.0	5.73	8938	14	32	46	kW
CH4 LFG		LFG	-35	14.000				1.0		1.0	3.82	6411	7	883	890	kW

																0	kW
Remains of ammonia prodcution		Utility	100	80.000		0.0		0.2	0.8		1.0	18.64	10833	56	1363	1419	kW
	1	Utility	95	1.013		0.0		0.2	0.8		1.0	18.64	276	1	1363	1365	kW
Combustion Air		Utility	15	1.013	0.2	0.8					1.0	75.00	0	0	0	0	kW
	3	Utility	1652	1.013	0.1	0.7	0.2			0.0	1.0	84.50	41277	969	63	1032	kW
Emissions		Utility	100	1.013	0.1	0.7	0.2			0.0	1.0	84.50	348	8	63	71	kW

Methane flow		Utility	15	1.013				1.0		1.0	2.88	0	0	665	665	kW
Air to combustion		Utility	15	1.013	0.2	0.8				1.0	57.60	0	0	0	0	kW
Emission		Utility	100	1.013	0.1	0.8	0.0		0.1	1.0	60.49	538	9	14	23	kW
From CHP		CO2	304	14.000	0.1		1.0			1.0	3.6	10011.45	10	18.6	29	kW
Oxygen		CO2	-35	14.000	1.0					1.0	0.18	6416.803	0	0.2	1	kW
	2	CO2	-35	14.000			1.0			1.0	3.42	8938.382	8	18.9	27	kW
	7	CO2	-35	14.000			1.0			1.0	21.13	8926.841	52	117	169	kW
	8	CO2	-27	150.000			1.0			1.0	21.13	9500.788	56	117	172	kW
Total CO2 for Urea Production		CO2	200	150.000			1.0			1.0	21.13	12560.79	74	117	190	kW