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Eco-efficiency assessment; Production of bleaching chemicals for the Elemental Chlorine Free, ECF, pulp industry

A Case study at Eka Chemicals (AkzoNobel Pulp and Paper Chemicals)

Master of Science Thesis in the Master Degree Programme Sustainable Energy Systems

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Abstract

Sustainable development embraces three dimensions and main areas; economic growth, social progress and ecological aspects. Eco-efficiency assessment is a business tool which can be used in order to compare two or several products, processes, activities or plants from an environmental and cost perspective. The tool is one way for companies to include sustainable development when it comes to future strategic decision making. Eka Chemicals is a business unit within AkzoNobel mainly producing and supplying chemicals and know how to the pulp and paper industry. The company is applying eco-efficiency assessments in order to learn more about their products and introducing life-cycle thinking in their organization.

The main objective with this thesis is to investigate the feasibility of developing a flexible model of alternative production systems and transfer it into Eco-efficiency assessments. A case study at Eka Chemicals acts as the basis for the thesis and it focuses on production processes for bleaching chemicals used by the ECF pulp and paper industry. A second objective is to increase the understanding of the bleaching chemicals production systems in terms of environmental and economic performance. Based on assumptions about; (1) the geographic location of the production and (2) system properties decision making at Eka can affect, four different production systems are compared in terms of eco-efficiency; (1) SVP-LITE, (2) SVP-SCW, (3) chemical island and (4) integrated plant.

It was found feasible to develop a flexible model for Eco-efficiency assessment. In the approach chosen, the systems are divided into background systems and foreground systems. Scenario analysis is applied and the scenarios are designed to distinguish background system properties from foreground system properties. This methodological choice makes it possible to identify important parameters and assumptions that affect the overall performance of the systems investigated. It further structures and speeds up the procedures since the assessment can focus on a certain part of the system at a time.

The alternative production systems studied show significant differences regarding the environmental impact dimension. When it comes to the economic dimension, it is not possible to differentiate and rank the alternative production systems by use of an eco-efficiency diagram.

The most important conclusion of the case study is that the assumption regarding how the electricity used for producing the bleaching chemicals, on the pulp mill site or elsewhere, is crucial for the ranking of the production systems compared. The chemical island is more eco-efficient if the electricity used is produced from biomass. When Russian electricity grid mix is used, the SVP-SCW scores best with regard to eco-efficiency.

It is further concluded that the geographical location of the production of ECF- pulp bleaching chemicals is a key parameter when trying to find the most eco-efficient alternative. The choice of producing sodium chlorate on-site or not is also an important parameter affecting the eco-efficiency of the production systems. Since transportations have a small influence on the eco-efficiency, the sodium chlorate is produced preferably off-site and transported to the pulp mill if the electricity system for on-site production is characterized by fossil fuels. If the on-site electricity system includes a large share of renewables, on-site production of sodium chlorate is preferred.

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1. Introduction

1.1. Sustainable Development and Life Cycle Thinking

Sustainable development is a concept which during the last ten years has gone from being an unfamiliar expression to one used daily in society. People in general have got an understanding for the concept but when asking people to explain it the answers differ a lot between individuals.

Sustainable development was defined in 1987 as a part of the report *Our Common Future* published by the World Commission on Environment and Development (WCED). It is also known as the Bruntland Commission or the Bruntland Report. In this document, sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987). The concept was further developed in the Rio Declaration. It was the result of the UN Earth Summit in Rio de Janeiro in 1992 and was created with the Bruntland Report as a basis. The Rio declaration contains 27 principles for sustainable development including the Agenda 21 for sustainable development and the Framework Convention on Climate Change (Rio declaration on Environmental Program).

At the World Summit on Sustainable Development in Johannesburg 2002 one of the three main objectives in order to reach a sustainable development was to promote a sustainable consumption and production of goods. The Johannesburg Plan of Action called for the Marrakech Process which is an international framework supporting the elaboration on sustainable consumption and production during a 10 year period of time. One of its main goals is to help corporations to develop greener business strategies (United Nation, 2010).

Sustainable development embraces mainly three dimensions and main areas; economic growth, social progress and ecological aspects. Business tools are required in order for companies to develop their products and processes towards sustainable development. Eco-efficiency assessment is a tool companies may use in order to evaluate their products or services from environmental and cost perspective. The tool provides the possibility to compare two or more products, processes, activities or plants in order to find the most eco-efficient alternative. An Eco-efficiency assessment is based on Life Cycle Costing (LCC) and Life Cycle Assessment (LCA). LCC is a method which assesses the cost performance of a good or product from an individual perspective, e.g. producer or customer. The LCA instead assesses the environmental impact caused by a product or a service. The assessments are based on life cycle perspectives, cradle-to-grave or cradle- to-gate (Borén, 2008).

The industry and especially the chemical industry has for long been forced to take actions to improve their environmental performance. At first end-of-pipe solutions was a standard procedure in order to decrease emissions. The end-of-pipe solution focuses on taking care of the emissions after manufacturing of the products. During the 1970s and forward environmental management developed from focusing on end-of-pipe solutions to develop solutions covering a broader perspective of environmental improvements. Environmental issues were considered at an early stage in the design phase of a process or product and were continually regarded in order to prevent the creation of emissions and waste. Further on, materials earlier regarded as waste became valuables and useful products (Löfgren, 2009). The new way of environmental management increased the attraction for life cycle thinking because of its potential of accomplishing environmental improvements. Life cycle thinking is defined as "a way of thinking that considers cradle-to-grave implications of different activities and products without going into the details of a LCA" (Baumann & Tillman, 2004).Life cycle thinking within an organization or a company may thus be an important way to increase the understanding of a product or a process from an environmental perspective during its entire life cycle. Including life cycle thinking in the phase of development of a product or a process makes it possible to choose directions and take decisions during the development in order to minimize the environmental loads caused by the product or process. Implementing life cycle thinking at different levels within an organization might encourage environmental awareness within the entire organization, and become a part of the organization itself.

1.2. Background

Eka Chemicals (AkzoNobel Pulp and Paper Chemicals) is a business unit within AkzoNobel mainly producing and supplying chemicals to the pulp and paper industry. The company is a world leading supplier of bleaching chemicals to both chemical pulp production and mechanical pulp production. Worldwide, Eka Chemicals manufactures performance chemicals for pulp and paper production as well as specialty chemicals for other applications. Eka Chemicals has 2 700 employees in 19 countries (Eka Chemicals, 2010).

Within AkzoNobel the Sustainable Development group is a department acting as an internal consultant firm offering services within sustainability to the AkzoNobel business units. One service the department provides is eco-efficiency assessments which may be used for strategic business decisions. In November 2008 an eco-efficiency assessment was performed comparing different concepts of producing and supplying an Australian pulp mill with bleaching chemicals used for pulp production. The facility was situated in Tasmania. The main goal of the project was to compare, through Eco-efficiency assessment, different alternatives of supplying the pulp mill with bleaching chemicals required for production of Elemental Chlorine Free, ECF, pulp. Three different concepts were investigated; (1) Chemical Island, (2) Integrated Plant and (3) SVP-SCW®[1] chlorine dioxide generator. The system boundaries were set to go from cradle to delivery at pulp mill. The functional unit in the project was set to the amount of bleaching chemicals required by the pulp mill for producing one million ton of pulp annually. The chemicals delivered to the pulp mill were hydrogen peroxide, chlorine dioxide, sodium hydroxide, sodium sulfate and hydrogen.

One conclusion from the eco-efficiency assessment conducted is that the ranking of the concepts is sensitive to the electricity mix used for production of the bleaching chemicals. Another conclusion is that whether or not by-products such as sodium sulfate and hydrogen can be utilized by the pulp mill impacts the result.

The production of bleaching chemicals to the pulp and paper industry are complex processes. The main output is indeed bleaching chemicals. However, chemicals produced internally in the process, are sometimes attractive. The concepts integrated plant and chemical island can both be designed to produce more sodium chlorate than required for production of the bleaching chemical chlorine dioxide. The excess of sodium chlorate is sold to the open market. If the market demand for sodium chlorate is high the production of the chemical may be increased. However, the market demand for sodium chlorate varies in different regions in the world. Therefore, the geographical location of the site may affect the ranking in terms of eco-efficiency of the different concepts.

The 2008 eco-efficiency assessment assumed export of sodium chlorate to the open market and for the integrated plant the chlorine alkali process was assumed to yield no excess chlorine. Further on, it did not assess how the geographical location of the production site affects the eco-efficiency performance.

This thesis was initiated since Eka Chemicals would like to be able to use the eco-efficiency assessment of some alternative production concepts of bleaching chemicals both for process development and in the communication with customers. To be really useful for these purposes, the model behind the eco-efficiency assessment has to be flexible so that input parameters can be varied from case to case. Already at the start, Eka Chemicals had ideas of what parameters they would like to vary in order to get a more useful model.

[1] SVP-SCW® is a registered trademark of Eka Chemicals in one or several countries of the world

Since eco-efficiency assessments are based on LCA and LCC, the reliability of a study is dependent on that:

- the systems boundaries are relevant and consistent; and
- the data used is correct and representative.

LCA is a tool which is being used by a wide range of practitioners. It is a popular tool when investigating the environmental impact caused by a product or a process. Nevertheless, LCA is often criticized for having limitations regarding the impact assessment and the interpretation of the results generated. It embraces data availability and quality, local environmental uniqueness and functional unit definition, among others (Reap, 2008). Further on, LCA is a linear modeling tool which makes it difficult to change process modeling variables without changing the model itself. Gäbel (2001) claims that the LCA process model usually is changed when investigating different configurations of a product or a process. It makes LCA to a limited and time consuming tool to use.

Eco-efficiency assessment compares different processes or products with regard to environmental impact and economy from life cycle perspective. The tool is used within industry and may be used to support decision making. However, the tool is often used to assess and compare existing products or processes. Eco-efficiency assessment (or eco-efficiency thinking) early in the development or design phase might increase the development of products or processes with higher eco-efficiency.

During the last ten years the importance of implementing LCA and/or eco-efficiency assessment during the development phase of new products or processes has been enlightened. Examples of research material within the topic may be found in Gäbel 2001 and Lövgren 2009. The need for flexible LCA models has grown, yet the knowledge and use of LCA during the development phase of products and processes is limited within companies. The companies have started to realize that the use of LCA during the development phase of products and processes may be beneficial. However, it is important that the environmental impact of a product can be simulated more easily and continuously during the development phase of a product or process in order to make LCA useful.

Optimization of existing products and processes is also an area where LCA may be of great interest for companies and producers. Since most of product and process development is performed using computer based programs, the output parameters have to be connected to the LCA tool in order to make it useful. Material and energy balances are example of parameters that are outputs from design or optimization tools that may be used and combined with LCA. It is of great importance that it is possible to make changes in the design or optimization program and quick and easily implement those changes to an LCA. Thus, it is possible to investigate if and how changes during the design process influence the environmental performance.

Further on, the environmental impact of a product or a process may be minimized through optimization, using a simulation tool. It may thus be possible to include environmental optimization as a design parameter when making strategic decisions of new or existing products and processes. Environmental performance may be one of many parameters when performing multi objective optimization of a product or a process (Gäbel, 2001).

Combining process simulation and LCA is under developing. One possibility would be to investigate if it is possible to combine process simulation and eco-efficiency assessment in order to identify efficient working procedures. The idea is to study literature within the subject and try to conclude, or at least investigate, if it is possible to apply on eco-efficiency assessments.

1.3. Purpose

The aim of the thesis is to investigate and develop a detailed and flexible model of alternative production systems and transfer it into an Eco-efficiency assessment. An Eco-efficiency assessment case study at Eka Chemicals will be performed and it will act as the basis for the thesis. The case study will focus on production processes for bleaching chemicals used by the ECF pulp industry.

A second purpose of the thesis project is to increase the understanding of the bleaching chemicals production systems in terms of environmental and economical performance.

1.4. Objective

The main goal with the case study is to compare different alternatives of producing bleaching chemicals to the ECF pulp industry, using eco-efficiency assessment.

A second goal is to investigate and analyze how the geographical location chosen for the production of bleaching chemicals affects the eco-efficiency of the different concepts. The goal is to identify the most eco-efficient production concept in relation to the different geographical locations investigated.

The third goal is to include flexibility in the modeling of the bleaching chemicals production systems. Different system settings will be investigated with the aim to identify key parameters which significantly affect the eco-efficiency performance.

1.5. Scope

The Eka eco-efficiency assessment case study is intended to be used to support strategic business decisions. It is also intended to provide information about the environmental and financial performance of the different production concepts. This information and the experiences can be used internally in process development but also externally in the communication with customers.

1.6. Methodology

The concept eco-efficiency and its methodology approach will be summarized in the literature review. LCA and LCC are introduced and the limitations with the methodology found in literature are reviewed. The idea is to introduce the reader to limitations which arises when trying to build a model within eco-efficiency which should include the flexibility of a production system. The literature review will further focus on how to build flexible life cycle models. The subject of interest is to investigate if it is possible and how it can be accomplished to build an eco-efficiency model which can include flexible features of a chemical process production system. Earlier studies have focused on Discrete Event Simulation (DES) of manufacturing processes and how the dynamics from the simulation may be interconnected to an LCA (Löfgren, 2009). Another study performed by Karin Gäbel (2001) investigated the potential for building life cycle inventory models in order to include the flexibility in the production process of cement.

Secondly an eco-efficiency assessment will be performed investigating the eco-efficiency of different concepts for production of bleaching chemicals for the ECF pulp industry. The literature review will act as a basis for the assessment which will give guidance on how to construct a more flexible model than the previous used in the eco-efficiency assessment performed 2008.

The LCA will be conducted using the LCA software Gabi 4.4 which is a mass flow modeling tool. The inventory results from Gabi will be transferred to an excel-based tool used for calculating eco-efficiency of the studied systems.

2. Theoretical frame of reference

2.1. Eco-efficiency

Eco-efficiency is a management concept which may be practiced by companies in order to encourage the search for environmental improvements. The philosophy encourages the society to take action for improvements which still must be economically beneficial for the commissionaire. The main goal of the business sector is to satisfy people's needs and be rewarded monetary if doing it successfully. Eco-efficiency therefore is a part of a society striding for sustainable development. The concept includes directly ecology and economy, two out of three elements included in sustainable development. The term Eco represents ecology and economy. Nevertheless, Eco-efficiency indirect includes the third element, social progress, through improving the environmental and economic situation in the society (Lehni, 2002).

The concept Eco-efficiency was invented in order to define the role of business and combine it with sustainable development. The term was coined in the report Changing Course which was an outcome of the Earth summit in Rio de Janeiro (Saling, 2002). Innovation and competitiveness within business combined with taking greater responsibility for the environment was the main driver and idea behind the philosophy (WBCSD, 1996)

The main idea with Eco-efficiency is to accomplish environmental improvements which are economic competitive to others. Further on, the objective is to become more efficient by creating more value while reducing material and energy consumption and thereby reduce the overall emissions. The following three objectives are defined by the World Business Council for Sustainable Development (WBCSD) regarding Eco-efficiency. (Lehni, 2002)

- Reduce the consumption of resources. The material and energy consumption should be reduced through enhancing recyclability. Producing products with higher quality and longer life times may also lead to improvements within the area.

- Reduce the impact on nature. Improvements can be performed using renewable resources which are sustainably managed as well as minimizing emissions, waste disposal and toxic substances.

- Provide customers with higher quality products and services. The customer benefit can be improved through providing the user additional services of the product such as e.g. functionality or/and increased overall life time. It is however important that higher customer benefit must not interfere with the two former objectives.

Eco-efficiency has become a widely used management concept among large companies worldwide (Kicherer, 2007).One mayor argument for measuring Eco-efficiency is that the result is interpretable on different levels within an organization. It may create knowledge of sustainable development throughout the entire organization of a company. Further on it can be used between companies, creating cooperation between those and thus include a products entire life-cycle. Another strong argument for applying Eco-efficiency is that companies actually start to regard and measure the environmental impact they create. If environmental improvements are achieved within a business due to that awareness, it may be used in marketing and communication with the companies ambitions for sustainable development (Saling, 2002).

However, the Eco-efficiency philosophy has received criticism since no absolute targets nor improvements e.g. resource consumption, is included. Critics argue that the real benefit of looking at Eco-efficiency does not always contribute to actual reductions of resource use and emissions. Further on, measuring Eco-effectiveness instead of efficiency might encourage continuous innovation and new technology instead of simply improving existing technology. Others claim that using fewer resources per output does not eventually lead to a more sustainable society. The main argument they present is that the consumption pattern is the crucial factor for sustainable development and not improved technology. If a product increases in value its Eco-efficiency might be high even if the environmental impact is high. (Lehni, 2002)

Eco-efficiency analysis, now referred to as Eco-efficiency assessment within AkzoNobel (EEA), is focusing on measuring the sustainability of a product or process (Saling, 2002). EEA:s are unique and are often adapted to fit the budget and the time frame allocated for an EEA project within a company. However, the project has to be reliable and include scientific references in order to attain trustable results and maintain the trustfulness of EEA:s. The result should further be easy to interpret in order to facilitate a conversation between involved parties and to make the EEA useful.

The chemical company BASF has created a method for how to conduct an EEA which provides a result that can be used for business decisions. The main goal with the method was to make a tool mainly useful for the chemical business but also for other businesses. The tool was constructed in order to be manageable by LCA-experts and understandable for people not working with sustainability. The method follows the rules for LCA methodology defined by ISO14040 ff but it also includes cost calculations connected to a product or a process life cycle.

Since Eco-efficiency may be measured in a variety of ways and different companies apply different methods a complete summary is beyond the scope of this thesis. However, AkzoNobel is applying the methodology that BASF has defined and it will be used in this thesis project. For this reason the article *ECO-Efficiency Analysis by BASF: The Method,* published in the International Journal of Life Cycle Assessment 2002, is summarized below. I recommend the interested reader to take part of this article since it pedagogically describes Eco-efficiency and the methodology.

2.2. Eco-efficiency assessment - the method used

An Eco-efficiency assessment is conducted through following a couple of standard routines. Firstly the customer benefit has to be defined and it acts as the reference when performing the assessment. Secondly, in order to make the comparison fair, all the processes studied have to be connected to the defined customer benefit. The customer benefit is also referred to as the functional unit in ISO 14040. Thirdly the entire life cycle has to be considered. Further on, an ecologic and an economic assessment should be carried out based on the life cycle of the investigated objects. As a final step health issues and risks to people connected to the customer benefit should be assessed.

The customer benefit is always a central part of an Eco-efficiency assessment. Since the same customer benefit often may be achieved using different products or processes it is possible to compare them to each other on an economic and environmental level. Therefore an Eco-efficient solution provides the customer benefit in a better financial and less environmental harmful way.

When the customer benefit is defined and the products or processes satisfying that benefit are included in the study the environmental impact should be determined. It is done using LCA methodology. The LCA methodology is summarized in the chapter LCA. The consumption of raw material, the energy consumption, emissions, the toxicity potential and the risk potential connected to the different objects studied should all be assessed through the entire life cycle. The result is categorized into different impact categories which are primary energy consumption, resource depletion, global warming potential, acidification potential, ozone depletion potential, photochemical ozone creation potential, emissions to water, waste, land use, toxicity and risk potential.

Since Eco-efficiency assessment only provides a comparable result and no absolute values the impact categories requires to be normalized to each other. The least favorable alternative is given value 1 which the others are set in relation to. In order to form a total value for the environmental impact a weighting scheme is made up combining relevance weighting factors and societal weighting factors.

The relevance weighting factor is calculated for each impact category. The relation between the environmental impact for the products and processes investigated and the total environmental impact in the investigated region e.g. a country is representing the relevance factor. If the contribution of e.g. the energy consumption connected to the product or process is large compared to the regional energy consumption, the relevance factor will be high and vice versa. The relevance factor is comparable to the normalization procedure within LCA.

The societal factor contributes with the societal view of the different environmental impact categories and how the society valuates different ecological impacst. Within LCA methodology this aspect is included in the weighting step. The factors are determined through surveys, public opinions and interviews with experts. BASF announces that their experience is that changing the societal weighting factor does not affect the final result significantly. However, the societal weighting factor can be changed in the future if the general opinions in society changes.

The overall ecological weighting factor for each impact category is calculated through multiplying the relevance factor and the societal factor to the power of 0.5. Normalizing the weighting factor for each impact category against the sum of weighting factors provide a result showing how much the different impact categories contribute to the total environmental impact.

In order to include economy in the EEA, a Life Cycle Costing (LCC) for each alternative providing the customer benefit has to be performed. The concept LCC is explained in the chapter LCC. A relevance factor for the different options is calculated by dividing the LCC result for one alternative with the gross domestic product in the current region e.g. a country. Since this value in most EEA:s is small the absolute value is not of interest. Nevertheless, the number can be used for comparative purposes.

The ecological result can be inserted in the environmental fingerprint by BASF which is a plot comparing the different alternatives on the basis of energy consumption, emissions, resource consumption, toxicity potential, risk potential and land use. The investigated options are normalized against the least favorable alternative. The fingerprint plot provides an overall view over the investigated options and points out which category where potential improvements are current or necessary.

Finally the environmental relevance factor is compared to the cost relevance factor. A quote between those two factors is created and if the value is above one it implies that the cost may be of importance. An analysis of the cost for the studied options may thus be significant. However if the quote is far below one, may the analysis instead focus on the environmental impact of the different options investigated.

The final result of an EEA is the eco-efficiency portfolio. It is a two-dimensional graph representing normalized cost on the x-axis and normalized environmental impact on the y-axis. The different options are plotted in the graph in regard to their environmental and economic properties. It is via the Eco-efficiency portfolio possible to rank the different options after their eco-efficiency. Since the values are normalized it is however not possible to identify any absolute numbers. The scale of the plot is reversed having low eco-efficiency in the low left corner and high eco-efficiency in the high right corner.

Kicherer (2007) concludes that the BASF eco-efficiency assessment method does not result in absolute values which describe the environmental and economic performance of products or processes. Neither does it contribute to performing environmental and economic goals defined by the company or other parties. However, EEA:s provide results on how the largest environmental benefit for satisfying a customer need to the lowest cost can be achieved. Accordingly, EEA:s is creating opportunities for companies to find paths towards a sustainable development.

2.3. Life Cycle Assessment, LCA

A Life cycle Assessment (LCA) is often defined as a study which is investigating a product´s or a service´s environmental impact during its entire life cycle. The product or service which is being investigated is defined as the functional unit or the customer benefit. The environmental impact is connected to the functional unit which the entire study circles around. An LCA includes extraction of raw materials, processing of raw material and products, transportation, use phase and finally waste disposal. The guidelines for how to conduct a LCA is defined in the norm ISO 14040 and ISO 14044. (ISO, 2006)

The methodology of performing an LCA follows four main steps. The first step is to define the goal and scope of the study (ISO, 2006). It is here the study is defined and described e.g. the purpose of the study and who the audience of the study is. Purposes may be for example to make an inventory of the environmental flows connected to a product or to locate environmental hot spots in the life cycle of a product. It is in the goal and scope where the functional unit is defined. Further on is the system boundaries of the study described, the impact categories subject of investigation is chosen and the quality of data, average or specific, is specified. (Baumann & Tillman, 2004)

The second step is to perform a Life Cycle Inventory (LCI) in which the products life cycle is modeled with a flow sheet model (Blom, 2010).The model is built based on the goal and scope. Environmental input and output data is collected during the LCI. The collected data is summarized and the material flows and emissions are calculated according to the functional unit and its life cycle. (Baumann & Tillman, 2004)

The LCI results are attributed to predefined impact categories during the third step of the LCA which is called the Life Cycle Impact Assessment (LCIA) (ISO, 2006). It is performed in order to make the LCI result interpretative and relate emissions and resource consumptions to well known environmental impacts. The different emissions and resource consumption are classified into different impact categories, for example global warming potential, resources consumption and acidification potential. The individual contribution of emissions and resource consumption to the certain impact categories are calculated in the characterization. (Baumann & Tillman, 2004)

In the fourth and final step of an LCA the result is interpreted. It can be done through comparing the results to similar existing studies (ISO, 2006). Further on, contribution to the total environmental impact in a certain region can be calculated, called normalization. It may give a hint if the lifecycle of the functional unit is widely contributing to different environmental problems in a region. (Guinée, 2002)

Life Cycle Assessment is a prominent tool for assessing the environmental impact of the life cycle of a product or a service. It is widely used within companies and in the academic world for making investigations regarding environmental effects when producing and consuming products and services. Further on is the tool and methodology approved by organizations such as International Organization of Standards and the Society of Environmental Toxicology and Chemistry (Reap, 2008). The strength with LCA is that it is a consistent tool which quantifies a variety of environmental substances and emissions (Udo de Hues, 2004).

However, LCA has also been criticized. Criticism against the goal and scope definitions, allocation methods, definition of system boundaries, the life cycle impact assessment and the interpretation of the results has been pointed since these are all subjective for the performer. It is also free for the performer to make decisions and assumptions which may affects the study greatly and can affect the trustfulness and the strength of an LCA and thus also the LCA methodology itself (Reap, 2008).

Reap (2008) highlights that LCA is a steady-state tool which can be used on systems without flexibility. However, environmental and industrial systems are not steady-state systems and a complete representation of these is not entirely possible. Dynamics in the environmental system is for example long ecological systems response times and the properties of transient environmental impacts over time. Flexible features in industrial systems are typical transience of technology and emissions control which not is accounted for in LCA methodology. LCA´s claims for environmental completeness will be closer to a realization if the dynamics of systems can be included.

The credibility of LCA methodology is of high significance since business decisions are taken based on LCA:s. The environmental impacts, of different alternative ways of creating a customer benefit, can be compared to each other and is in some companies a major argument for making an investment in a particular alternative. But since the dynamic features of an industrial system are difficult to capture, people might be sceptical to make business decisions based on LCA: s.

In 1996 Kniet et al concluded that LCA might be a suitable tool for process design. The conclusions were true and LCA can today be used for process design, including process optimization. One example is when Bauer (2004) built a model optimizing the environmental impact connected to a chemical process using the process simulation tool Hysys.

2.4. Life Cycle Costing, LCC

The cost is always a central subject when companies develop and construct new products. Between 75 and 80 per cent of the total life-cycle cost is determined in the design phase of a product. The cost can be reduced through analyzing the life cycle cost of a product during design phase (Aseidu, 1998). Reibizer and Hunkeler (2003) define LCC, as an "assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in a product life cycle". It includes actors within the supply chain, the producers, the user and consumer as well as the end-of-life actor. The life cycle includes the design phase, the production phase, the usage phase and finally the disposal/recycling phase. Customers and producers may use LCC: s for different analyses depending on which phase of the product/service life cycle affect them. It can be used for comparing different competing systems, compare the long term cost of a project with a given business budget, investigating maintenance costs and warranty costs as well as comparing sales strategies depending on sales price and quality (Barringer & Weber, 1996).

Questions have been stated and discussions have been held regarding whose cost the LCC should be focusing on. Possible stakeholder may be the producer, the user/consumer or the end-of-life operator. Since the cost for one actor is the revenue for another the LCC results will differentiate in between the different cases. Margins will be added for each stage in the life cycle as well as the value of the product. A user of a product is mostly interested about the cost for purchasing the product, the cost for using the product and the cost for disposing it. To differentiate the costs in the raw material production and the production of the product is not of importance for a customer. On the other hand, if a producer is performing an LCC for one of its products the interest in differentiating the costs in the former part of a products life cycle is highly important. Especially when the revenue from selling the product may be increased due to unnecessary costs in the production phase. The system boundaries for LCC:s performed by producers are therefore often limited to cradle-to-gate studies instead of cradle-to-grave studies (Rebizer & Hunkeler, 2003)

Life cycles costs can be differentiated between internal costs and external costs. Internal costs are all costs and revenues that are connected to the economic system which is explained by Rebizer and Hunkeler (2003). The cost can be set in direct connection to a product or service life cycle. Internal costs include production costs, transportation costs, cost for using the product and the cost for taking care of the product in its end-of-life. Due to the nature of the internal costs, these may be assigned to the owner of each products´ or services´ life-cycle stage. Nevertheless, external costs, also referred to as externalities, are costs that cannot be linked direct to a producer or a consumer of a product or a service. It includes costs that occur due to environmental and social impacts. Producers and consumers causing the environmental and social impacts thorough their action do not usually have to pay for it directly. An example is air pollution which daily affects people worldwide (Rebizer & Hunkeler, 2003). The polluters are not charged. However external costs are often paid for via society or by future generations (Klöpffer, 2003).

According to Reibitzer (2003) the internal costs are differentiated to the economic system. The external costs are recognized outside the economic system but inside the social and environmental system. If an LCA and an LCC both are applied on a product or a service there is a risk for counting the external cost twice. Since the system boundaries of an LCA are the system boundaries of the social and environmental system the externalities may be included as a monetary unit in the LCC and as an environmental unit in the LCA (Klöpffer, 2003). In order to avoid counting externalities twice the system boundaries of the LCC can be set to the economic system boundary and the system boundary of the LCA can be set to the social and environmental system boundary. Nevertheless, double counting of external costs are difficult to avoid when combining LCC and LCA, since the monetary cost of a product or a service often includes external costs via e.g. taxes (Rebizer & Hunkeler, 2003).

In order to combine LCA and LCC into a useful and reliable tool which measures sustainable development, the system boundaries and the functional unit of each tool needs to be adapted to fit each other (Hunkeler & Rebitzer, 2005). One argument presenting the importance of being accurate when adapting the system boundaries is described above.

2.5. LCA Modeling

The idea with this chapter is to introduce the reader to LCA modelling and basic methodology approaches used. Background/foreground system approach is often used in LCA studies but the reason for using the approach is seldom explained. This is reviewed in next chapter.

There are two types of LCA, the descriptive LCA and the change-oriented LCA. A descriptive LCA, also referred to as the accounting LCA, is performed in order to describe an existing or future life-cycle of a product or a service (Guinée, 2002). The purpose of conducting a descriptive LCA is to assess the magnitude of the environmental impact referred to the functional unit investigated. The methodology embraces the completeness of a system and thereby is average system and process data mainly used (Baumann & Tillman, 2004).

A change-oriented LCA is on the other hand practiced in order to investigate the difference between changes in a system (Guinée, 2002). Its main purpose is to investigate how changes within the system boundaries affect the overall environmental performance (Baumann & Tillman, 2004). The method can be used for predicting the consequences for a certain action and may be used as an argument when strategic decisions are about to be made (Guinée, 2002). It is important to keep in mind when dealing with LCA:s that the complexity of the real economic, socio and technical system can never be modeled without uncertainties. A model is defined by Gustafsson (1996) to represent a system, chosen by an actor, which depicts essential properties of system. The idea of modeling is that conclusions can be drawn using the model which corresponds to the system, even though it includes fewer elements and relations (Guinée, 2002).

When applying change-oriented LCA a reference model first is created. The reference model is the model representing the system investigated. It can be a real system as well as a fictive system. The reference model act as benchmark for testing theoretically created scenarios. It includes the possibility of analyzing theoretical changes of the studied system.

Sandén et al (2005) developed the methodological approach of LCA and introduced three options to choose between when selecting LCA methodology. They distinguish the classifications between responsibility, time and technical generality. The state-oriented or the change-oriented approach is defined under the heading responsibility. In a state-oriented LCA the studied object is responsible for a share of the total environmental effect, in a steady-state. In an effect-oriented LCA is the studied object instead responsible for the environmental impact caused by a change from the defined steady-state. The time frame of the study should be chosen between looking back at former environmental impacts (retrospective) or predicting future environmental impacts (predictive). The technical generality should be selected based on if the LCA is focusing on a product or a technology. Sandén & Karlström concluded (2007) that the traditional descriptive approach is suitable when investigating a technology or a product in a steady-state in the past, present or future. In order to evaluate consequences of new systems the prospective attributional LCA is recommended. Accordingly, I think the most appropriate modeling approach to use in this case study would be the descriptive approach. The systems I will be modeling are future steady-state systems.

2.6.1. Background and Foreground system

When constructing a model to be used in LCA, it is useful to divide the system in a background system and a foreground system. The foreground system represents the part of the system which is related to the process investigated. The state of the process can be changed by actor's decisions which affect the energy and mass balances in the system. The background system is the part of the model which indirect is affected by actor's decisions in the foreground system. The system is not completely static since it adapts due to changes in the foreground system, however, the adoption is mainly considering mass balance expansions (Baumann & Tillman, 2004).

Dividing a system into a background and a foreground system may be useful and has considerable advantages. It can be useful when investigating if the actor controlling parts of a system is the dominant source of the total environmental impact compared to the background system. It therefore can act as a reference in order to conclude on what part of a system an LCA study may focus upon and where the largest potential for improvements may be. Further on, focusing on a small part of a system may be time and cost efficient. Further on, it can preferably be used on a company level defining the foreground system to include a gate-to-gate system, the system which the company controls. Nevertheless, the foreground system can be expanded to include the suppliers of raw materials including a cradle-to-gate study. However, to expand the foreground system to include a cradle-to-gate study requires that the company in focus can affect their suppliers directly or at least within a near future.

Löfgren (2009) constructs a model consisting of multiple system boundaries representing the production of bearing units by SKF. The traditional foreground system, described above, is expanded to include a cradle-to-gate system. The cradle-to-gate system is further divided into smaller systems and different functional units are used for each sub system in the LCA study. Löfgren is confirming, with his work, that it is possible to use a flexible foreground/background system approach in order to include the suppliers in the foreground system. (Löfgren, 2009)

The data describing the foreground system should be gathered on a steady-state basis and the best available data should always be used. For existing systems physical data often exists, although it is an effort to collect the data. When future systems are about to be analyzed steady-state data is often missing. Data can instead be collected from laboratory tests or computer simulation models. A sensitivity analysis is recommended in order to evaluate the sensitivity of the system. In prospective studies where largely growing technologies are represented, which indirect with time may change the background system, predicted average data is suitable. (Hospido, Davis, & Berlin, 2010)

2.6.2. Scenario analysis

The Society of Environmental Toxicology and Chemistry (SETAC) 2005 defines a scenario within the LCA context as "*a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future and, when relevant, a description of a path from the present to the future*". Each scenario is developed in the goal and scope definition of the LCA and should include the technosphere, the ecosphere or the valuesphere. There are two main types of scenarios to choose between within LCA methodology, the what-if scenario or the cornerstone scenarios. (Ekvall, 2005)

The what-if scenario is used for comparing multiple well-known options to each other. A what-if scenario is often used for testing specific changes within a system and the environmental consequences. It can be useful in decision situations e.g. for companies. However, it is important that the scenario creator is familiar with the studied field in order to construct scenarios based on science and relevant assumptions (Ekvall, 2005).

Cornerstone scenarios are often used in order to get the practitioner to investigate a system on an overall level. This methodology does not usually yield quantitative results. Instead it is used to get an overall view of a studied area and provide recommendations of in what direction the development of the studied subject proceeds. The result can be used for planning future research or long term strategic planning. (Pesonen, 2000)

For the eco-efficiency study it seems reasonable, at this stage, to implement what-if scenarios to investigate parameters which might affect the eco-efficiency for the studied alternatives.

2.7. Difficulties with modeling

The definition of a model given by Gustavsson (1996) includes the importance of capturing the essential properties of the real system when building the model. It further stresses the importance of that conclusions can be drawn regarding the real system, based on this model. One of the limitations of model building within LCA is that the models created do not always represent the properties of the studied system sufficiently. This is not an essential problem when the outcome of the LCA study is informative and the audience mainly are interested in using the result for learning on a highly resolute level about its system. The problem arises when the result from the study has to be accurate, e.g. in order to be used for strategic business decisions within a company.

Three weaknesses have been briefly mentioned in the previous chapter of the report concerning the problems that may arise when building reliable LCA models. Firstly, the data quality used must be of high quality as well as it has to be easily available (Isofis, Hanrot, Birat, & Abilitzer, 2010). Since inventory data can be difficult to collect and data for future processes is limited data quality certainly limits the usefulness of a LCA model. Secondly, the dynamics of the system investigated in LCA is often difficult to capture sufficiently since linear modelling characterises LCA. Thirdly, optimization of environmental properties of a system has become interesting lately as well as including environmental properties as one parameter in multi-objective optimization. It requires the LCA model to be flexible in the sense of data input change and system changes. Since the flexibility of LCA models is limited the possibility of using LCA for optimization is limited.

The following three chapters embrace the weaknesses introduced above. The idea is to introduce the reader and create awareness regarding those difficulties, but also bring up studies where those types of problems have been handled and solved.

2.8. Quality of data

The quality of data used in the LCI is an important parameter when investigating the reliability of an LCA study. In order to describe a system with a model the input data must be of high quality and relevance. Properties that can affect the quality of data are the age, the geographical and technical coverage of the data. Collecting precise data can be time consuming and costly. Especially for future systems data might be missing and finding theoretical data in the literature can be very time consuming. LCA practitioners is confronting these problems regularly, therefore more advanced ways of collecting data are under development. (Isofis, Hanrot, Birat, & Abilitzer, 2010) One way is to use process simulation.

The steel industry has during the last years involved LCA, via Eco-efficiency, in their product development and design phase of the steelmaking route. The goal is to decrease their emissions on green house gases (GHG) in order to meet the Kyoto protocol requirements. The steelmaking route consists of a number of different processes which can be fitted together in different constellations. However, the LCA practitioners were not able to conduct the assessment since the quality of the data was low or missing. In order to find data they developed a model which combine physiochemical modelling and LCA. A model of the steal making route, including the different internal processes, was built in Aspen Plus, a commercial flow-sheet modelling software. Based on chemical reactions, thermodynamic laws and mathematical equations, Aspen Plus calculates the reliable inventory data needed in order to perform the LCA. It was concluded in the study that combining physiochemical modelling and LCA is a powerful tool in order to provide reliable LCA results with gate-to-gate system boundaries. A further conclusion in the study was that the model can be used in order to rapid companies work with mapping the environmental impacts of different industrial configurations. (Isofis, Hanrot, Birat, & Abilitzer, 2010)

A similar, however different, approach is recommended by Lund et al (2010). They have been investigating environmental consequences due to marginal electricity production using detailed energy system analysis (ESA). ESA is used in order to calculate the yearly average marginal technology within future energy systems. The inventory data was collected from Ecoinvent and is based on the yearly average marginal technology. The model provides a reliable future energy scenario via simulation with ESA and the environmental impact is calculated based on that simulation using LCA. The data used in the inventory analysis is reliable since the future marginal electricity scenario is simulated using an acknowledged simulation approach. Combining the simulation result with the Ecoinvent database provides a reliable assessment of the future.

Arguments for combining process simulation and LCA, in order to provide accurate LCI data, is also recommended by Bojarski et al (2010). A process simulation of three chemical processes is used as a case to illustrate how to generate reliable data for performing an LCI and assess the environmental impact of the processes.

2.9. Flexible features

As mentioned above, the flexible feature of a system is difficult to capture in basic LCA modelling. The problem is obvious when the environmental impact should be assessed for e.g. a flexible chemical process or a flexible manufacturing system. The question that arises is what static state of the investigated system should be chosen in order to properly evaluate the system. Sensitivity analysis including many static-states of the system is a solution commonly used.

In order to include the flexible properties of systems into LCA some different approaches have been considered. One way to capture flexible features of a system is to divide it into a background and a foreground system. The idea is described in the chapter background and foreground systems. Gäbel (2001) used the approach in order to develop a flexible model, representing a process for producing cement. The cement production system was divided into a foreground system representing the cement manufacturing and a background system representing the up-stream processes, outside the manufacturing process. The background system was analyzed using a traditional LCI approach. However, the foreground system was modelled using a physical modelling and object oriented modelling approach. It was concluded that the modelling procedure enhanced model flexibility and using it together with a simulation tool a flexible and useful model of a cement manufacturing process was created. (Gäbel, 2001)

The complexity and the flexible features of a system can be well captured using only process simulation tools. The process simulation tools simplify the model building process since e.g. chemical processes can be represented and modelled with softwares. The complexity of the system is automatically handled by the software. Reliable inventory can be generated for use to assess the environmental impact caused by the system. It further enables the user to easily simulate different modes of the system and via LCA the environmental impact caused by those modes can be analyzed (Bojarski, 2010)

The capacity of a process simulation tool in terms of its ability to capture and handle the complexity of a system is demonstrated by Morais (2010). He and his co-workers have investigated and compared the environmental performances of three different industrial processes used for producing bio diesel. The process system was modelled in Aspen Plus and the environmental result was analyzed using LCA. Aspen Plus lacked some thermodynamic properties to model the processes. These properties were estimated. Even though, the working procedure was very much simplified using the process simulation tool, as well as the possibility to capture the complexity of the processes. (Morais, 2010)

Similar conclusions are stated by Iosofis (2010), who were responsible for investigating the environmental performance of the steelmaking route described above. He concluded that the complexity of the steelmaking route is well described by the simulation tool used, especially concerning the gas and waste recycling system. He further concluded that the capability of the software for capturing the complexity of the system very much simplifies the environmental investigation and adds a further dimension of reliability to the study.

Löfgren (2009) uses the idea of combining LCA with process simulation in order to investigate the environmental impact caused by a manufacturing line at SKF. The goal of the study was to investigate if it is possible to point out whether the environmental impact caused by the production line is changing due to operators decisions. In order to capture the dynamic features of a manufacturing system discrete-event simulation (DES) was applied. DES is commonly combined with LCA used for conceptual evaluation of manufacturing system. The system is modelled with DES resulting in an inventory of the energy and material use including the changes in the consumption due to varied parameters. The conclusion from the study is that the static characteristics of the LCA is avoided by using the DES approach.

The five examples demonstrated in this chapter combines process simulation and LCA in order to include system´s flexible features into environmental systems analysis.

2.10. Optimization

Using process simulation together with LCA does not only contribute to reliable and easily collected inventory data and the possibility to analyze flexible features of a process system. It also contributes to the possibility to optimize existing systems in relation to the environmental performance. Either by comparing different configurations environmentally from the simulation tool or by using advanced optimization algorithms.

The SKF study, described above, used process simulation (DES) and LCA in order to analyze the environmental impact caused by changes in the production system. Based on the results it was possible to conclude if and how the different system configurations affected the overall environmental impact. It was possible to conclude the configuration that had the smallest impact on the environment. (Löfgren, 2009)

The model built by Gäbel (2001), was used for simulating the environmental performance, the product performance and the cost performance of cement manufacturing. The model can be used in order to investigate how the three performances change due to different configurations in the production process of cement. Evaluating how specific configurations of the process affects the overall result on the basis of environment, product performance and cost makes it possible to identify the most preferable option. Since three parameters are in focus a desired configuration for achieving best environmental performance might be undesirable regarding the product property and cost. Nevertheless, the methodology and the model can be used in order to optimize the production process of cement.

Process simulation, optimization and LCA are combined in a study where the environmental impact of dairy products is minimized. Different scenarios for the supply chain and the supply of future dairy products were constructed and simulated using the tool system analysis of food processing (SAFT).

The environmental performance of the different scenarios was calculated through LCA (Sonesson, 2003). The idea of optimizing the production sequence in a dairy based on environmental performance, waste minimization, was born when the results from the LCA were evaluated. The optimization of the production sequence was performed through a heuristic optimization approach. The approach minimized the dairy waste which turned out to be the production sequence with lowest environmental impact (Berlin, 2005). The dairy study is a good example where LCA is combined with several other approaches in order to optimize the environmental performance of a system.

The three studies referred to combines process simulation and LCA. This is done in order to find the system´s best parameter setting in order to minimize the environmental impact created by the system. Combining process simulation and LCA seems to be one approach to handle flexible systems in order to find an optimum setting and minimizing the systems environmental impact.

3. Case study at Eka Chemicals - Eco-efficiency assessment; production of bleaching chemicals used for elemental chlorine free (ECF) pulp production

3.1. Concepts included in the Eco-efficiency assessment

Pulp and paper industries are situated worldwide. The conditions for chemical production companies supplying the industry with chemicals are very dependent on the infrastructure and the political situation in current regions. Since the pulp and paper industry is dependent on e.g. bleaching chemicals in order to attain a constant production it is absolutely necessary that chemicals are continuously supplied. In order to ensure the supply of bleaching chemicals used for production of pulp, constellations may be installed to produce a number of chemicals on-site. The risk for deficits of chemicals required for the production can be minimized via on-site production.

The production of ECF pulp requires a mix of pulp bleaching chemicals. Chlorine dioxide and hydrogen peroxide is used for bleaching the pulp, however sodium hydroxide, sodium sulfate and sulfuric acid are chemicals also used in the process. Eka Chemicals is producing pulp and paper chemicals. Chlorine dioxide and bleaching chemicals for ECF pulp production is the company's main area. The company is a supplier of chlorine dioxide plants and has developed a number of different process technologies.

The SVP-LITE®[2] and the SVP-SCW are stand-alone chlorine dioxide generators producing chlorine dioxide, which is used for ECF pulp production, and sodium sulfate. The generators are installed on-site close to a pulp mill. The reason is that chlorine dioxide is not preferably transported. Chemicals produced by the generators are utilized in the pulp mill. However, on-site production of ECF pulp bleaching chemicals using stand-alone chlorine dioxide generators requires additional supply of bleaching chemicals as well as raw materials used in the generators.

A chemical island and an integrated plant are more complex installations than SVP-LITE and SVP-SCW. The two concepts are sets of production units, including chlorine dioxide generators, interconnected to each other. The concepts produce and supply several different chemicals on-site. A chemical island includes fewer processes than an integrated plant and therefore produces fewer chemicals. Placing a chemical island on-site near a pulp mill offers the possibility of producing a variety of bleaching chemicals within the chosen scope. Still some bleaching chemicals and raw materials have to be additionally supplied from off-site production. An integrated plant is an alternative way for production of bleaching chemicals. The plant offers the possibility of producing the entire mix of bleaching chemicals required for ECF pulp production. Raw materials have to be supplied from off-site production, however the required chemicals are basic chemicals common on most markets worldwide e.g. sodium chloride.

The production processes introduced above is described in more detailed level below. The idea is to introduce the reader to the four production concepts which will be investigated in the eco-efficiency study. A general overview of production processes for chlorine dioxide is given by Vogt et al (2010).

3.1.1. Single Vessel Process LITE, SVP-LITE

The Single Vessel Process LITE (SVP-LITE) is a process concept for producing bleaching chemicals to the pulp and paper industry. It is a stand-alone chlorine dioxide generator producing chlorine dioxide which is used in the production of ECF pulp. By-products produced by the plant are sodium sulfate and sulfuric acid.

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[2] SVP-LITE® is a registered trademark of Eka Chemicals in one or several countries of the world

The process is based on the reaction of sodium chlorate, sulfuric acid and methanol. The main reaction in the SVP-LITE is the reaction of sodium chlorate to form chlorine dioxide. The generator solution is evaporated by means of a heat exchanger and sub-atmospheric pressure resulting in that water vapor and chlorine dioxide gas are leaving the generator. The water vapor and the chlorine dioxide gas are cooled in the condenser and water is condensed, enriching the chlorine dioxide concentration of the gas. The gas is finally forced into close contact with water forming a aqueous solution of chlorine dioxide. The solution is pumped to tanks for storage. (Eka Engineering, 2010)

The tail gases leaving the absorption tower, where the chlorine dioxide gases are forced into contact with water, are washed in a scrubber. Vent gases from the process are also being processed in the scrubber in order to increase the recovery rate of chlorine dioxide.

In the chlorine dioxide generator sodium sesquisulfate crystals, which is an acid version of sodium sulfate, are filtered for removal as a nearly dry solid. Chemicals trapped in the salt cake are washed and dissolved by hot water and returned to the main process. The sodium sesquisulfate salt cake is finally dissolved in hot water. It may be used by the pulp mill recovery system as sodium and sulfur or used for acidification purposes in the bleaching process of pulp. (Eka Engineering, 2010)

In the SVP-LITE process the by-product separated on the filter is sodium sesquisulfate, $Na_3H(SO_4)_2$. When the salt is dissolved, an acidic solution of sodium sulfate, Na_2SO_4, is created. If the Na_2SO_4 can be utilized with acid properties at the pulp mill it may be delivered without neutralization. Otherwise the Na_2SO_4 is neutralized typically using sodium hydroxide before being supplied to the pulp mill. A deficit of sodium sulfate is sometimes current on the local market near-by the pulp mill. Sodium sulfate can thus be put on the local market and sold to off-site customers. The SVP-LITE process is not used when supplying sodium sulfate to the market since the product is acid and has to be further processed before delivery (Vogt, Balej, & Bennett, 2010).

3.1.2. Single Vessel Process Salt Cake Wash, SVP-SCW

A Single Vessel Process Salt Cake Wash (SVP-SCW) is a stand-alone chlorine dioxide generator for production of chlorine dioxide. The process is similar to the SVP-LITE process but has an “add-on” to the process. The add-on includes an extra salt cake wash stage and is used in order to separate the sodium sesquisulfate into its sodium sulfate and sulfuric acid components.

The sodium sesquisulfate from the generator solution is filtered in a first stage filter and the salt cake generated is transferred to a metathesis tank. The slurry from the separation process is filtered in a second salt cake wash where the sodium sulfate crystals are recovered. The filtrate from the slurry is fed back into the generator or used elsewhere in the plant. (Eka Engineering, 2010)

As mentioned, the sesquisulfate precipitated in the generator is re-crystallized and washed twice on a first and a second filter. The Na_2SO_4 separated off the second filter is normally dissolved to a solution used by the pulp mill, but can also be placed into the market. The acid solution produced when washing the Na_2SO_4 is returned into the ClO_2 process. However it is a weak acid solution containing a lot of water which requires steam in order to concentrate the solution before being returned to the main generator (Vogt, Balej, & Bennett, 2010).

3.1.3. Chemical Island, C.I.

A chemical island is a concept producing, storing and delivering chemicals to a pulp mill. It embraces a variety of installations depending on its main scope, financial and environmental requirements. The focus for a chemical island can be to receive and supply chemicals to the pulp mill, but also including on-site production of chemicals.

The chemical island described in this chapter has similar scope as compared to the scope of the case study. It consists of a unit for production of chlorine dioxide, a unit for production of sodium chlorate, and a unit for production of hydrogen peroxide. The sodium chlorate produced is used as a raw material in the chlorine dioxide generator and the hydrogen (a by-product from the sodium chlorate unit) may be used for production of hydrogen peroxide or as an energy carrier.

The sodium chlorate unit generates sodium chlorate using sodium chloride, sodium hydroxide, hydrochloric acid and catalytic amounts of sodium dichromate. The production is a multistage reaction. A brine solution (water saturated or nearly saturated with sodium chloride) is introduced to an electrolyte process. The electrolysis generates hydrogen and sodium hydroxide on the anode and chloride at the cathode. The chlorate is formed through two parallel reactions. Primarily through autoxidation of hypochlorite in the bulk electrolyte and as a side reaction through anodic chlorate formation. Autoxidation is preferred by the industry since the consumption of electricity in the electrolysis process is dimidiated compared to anodic chlorate formation. The chlorate may either be collected as a crystal or used directly on-site for production of chlorine dioxide. (Vogt et al. 2010)

Hydrogen is generated as a by-product from the sodium chlorate production and can be used for production of hydrogen peroxide. The hydrogen may also be utilized as energy in the pulp mill or ventilated to air. Moreover, the sodium chlorate plant requires steam as a second energy carrier. (Vogt et al. 2010)

The sodium chlorate produced is introduced into the chlorine dioxide generator. The chlorine dioxide process used on a chemical island is preferably an SVP-SCW or a SVP LITE. An SVP-LITE may be installed if the pulp mill is able to utilize acid sodium sulfate. Otherwise an extra amount of sodium hydroxide has to be consumed in order to neutralize the sodium sulfate solution. It may also be chosen when there is no need for producing an extra amount of sodium sulfate for the market. The SVP-SCW may on the other hand be installed if export of sodium sulfate is wanted. The SVP-SCW consumes a smaller amount of sulphuric acid than an SVP-LITE. However, the process consumes a larger amount of steam than an SVP-LITE and the investment cost is higher. The choice of SVP process is therefore very dependent on the investment cost in comparison to the running cost (Björkman, 2010).

It is possible to construct a sodium chlorate plant which produces a larger amount, of the chemical on-site, than needed to satisfy the demand from the chlorine dioxide production process. The chemical island concept may thus be used to both satisfying the on-site pulp mill with bleaching chemicals and the market demand for sodium chlorate.

The hydrogen peroxide unit is not included in the chemical island investigated in the eco-efficiency assessment. Thus an explanation of this process is excluded.

3.1.4. Integrated Plant

Hydrochloric acid can be used as reducing agent in the production process of chlorine dioxide. It can further be used as a chemical for producing sodium chlorate. The need for any other strong acid is not necessary in order to produce bleaching chemicals for pulp production if hydrochloric acid is used. Thus, it is possible to integrate a chlorine dioxide generator with a chlorate and a hydrochloric acid plant. This constellation forms an integrated plant. Using hydrochloric acid as reducing agent in the chlorine dioxide production process creates a large amount of elemental chlorine as a by-product. Chlorine is a product which is undesired because of its properties of harming the environment. However, through using strippers and hydrogen peroxide the amount of elemental chlorine can be decreased to a level representing the production of chlorine dioxide using methanol based production. (Vogt et al. 2010)

An Integrated Plant consists of five main units. (Vogt et al. 2010)

- chlorine-alkali plant which produces chlorine, hydrogen and sodium hydroxide (caustic soda).
- hydrochloric acid burner in which the produced chlorine and hydrogen in the chlorine-alkali plant and the chlorine dioxide generator respectively are converted to hydrochloric acid.
- hydrogen peroxide unit using hydrogen generated from the system.
- chlorate plant where sodium chlorate is produced.
- chlorine dioxide generator and an absorption tower with a stripper where chlorine dioxide is produced and cleaned. The amount of elemental chlorine in the chlorine dioxide is reduced in the stripper and by using hydrogen peroxide as a cleaning chemical.

The production of sodium hydroxide, chlorine and hydrogen takes place through electrolyte in the chlorine alkali process. A brine solution is fed to the anode and sodium hydroxide water is fed to the cathode. When DC-current is applied to the cell, chlorine gas is formed at the anode and hydrogen gas and sodium hydroxide is formed at the cathode. The sodium hydroxide produced may be concentrated in an evaporation system in order to satisfy market quality. It can either be delivered to the pulp mill or used internally in the processes. (Vogt et al. 2010)

The chlorine gas and the hydrogen generated in the chlorine alkali process are used as chemicals in the hydrochloric acid burner and in the hydrogen peroxide plant. In order to produce hydrochloric acid, chlorine and hydrogen gas are introduced in the combustion chamber of the plant in which hydrochloric gas is formed. Hydrochloric acid is formed when the hydrochloric gas is absorbed by process water. (Eka engineering, 2010)

By-product sodium chloride from the chlorine dioxide generator is introduced in the sodium chlorate plant together with water. The exchange of sodium between the chlorate plant and the chlorine dioxide generator is not fully balanced and the need for extra sodium is introduced in the brine bleed from the chlorine alkali process. However, hydrochloric acid and sodium hydroxide is produced internally on-site by an integrated plant and not delivered from an external source as for chemical island.

The chlorine dioxide generator installed on an integrated plant, SVP Total-HCl, differs from the unit used on a chemical island. Instead of using methanol as a reducing agent the process utilize hydrochloric acid. The hydrochloric acid is produced on-site and the need for any other strong acid produced off-site is not needed. (Vogt et al. 2010) The chlorine dioxide gas from the generator contains the very significant amounts of elemental chlorine, which saturates the chlorine dioxide solution with elemental chlorine. To avoid the elemental chlorine to reach the bleachery (where it would cause a negative impact on the environment) it can be decreased using a stripper possible in combination with hydrogen peroxide.

Like for the chemical island a hydrogen peroxide unit is not included in the integrated plant investigated in the case-study. Thus, an explanation of this process is excluded.

The integrated plant constellation and its processes can be designed in different ways dependent on the properties of the surrounding system. Firstly, the chlorate plant can be dimensioned for production of chlorine dioxide. It can further be dimensioned to cover production of sodium chlorate for both the chlorine dioxide generator and an external market demand. Secondly, the chlorine-alkali process can be dimensioned in order to satisfy the demand for chlorine in the hydrochloric acid burner. An integrated plant with this setting is producing a deficit of sodium hydroxide demanded by the pulp mill and the deficit is covered by off-site production. The dependency of external suppliers is avoided if the chlorine-alkali process instead is dimensioned in order to cover the pulp mill need of sodium hydroxide. In this case an excess of chlorine is generated by the system which not is demanded on-site. This chlorine can be sold to the market.

3.2. Goal and scope – case study

3.2.1. Purpose and objective

The goal of the case study is to assess and compare the eco-efficiency of alternative concepts for producing bleaching chemicals for the Elemental Chlorine Free, ECF, pulp industry. The following four production concepts are compared from an environmental and economic perspective:

1. Chlorine dioxide generator type SVP-SCW
2. Chlorine dioxide generator type SVP-LITE
3. Chemical Island, C.I.
4. Integrated Plant, IP

The assessment and comparison are first carried out for the supply of bleaching chemicals to a specific pulp mill in Russia. Second, possible key parameters and assumptions are varied in order to identify flexible parameter settings significantly affecting the eco-efficiency. Third, the geographic location of the pulp mill is varied in order to find out how this affects the eco-efficiency.

The intended audience of the eco-efficiency assessment is Eka Chemicals. It is Eka Chemicals who has commenced the project in the first place. Further on, the study may be of interest for the pulp & paper industry, environmental authorities and NGOs interacting in regions where the products and services of Eka Chemicals may be implemented.

The eco-efficiency assessment is performed in order to provide Eka Chemicals with information about the environmental and financial performance of the alternative concepts to provide a pulp mill with ECF bleaching chemicals. The knowledge will be used for educational purposes by the organization working with process development. It will give employees at Eka Chemicals a better understanding of environmental and economic issues related to their processes and products. Eka Chemicals also aims for using Eco-efficiency assessments:

- in strategic business decisions such as investments; and
- for providing information to a customer about a specific production site and to identify the most optimal production concept for the specific site.

3.2.2. The Function

The production of bleaching chemicals for an ECF pulp mill is the basic function of the studied system.

3.2.3. Functional Unit

The functional unit of the eco-efficiency assessment is the amount of bleaching chemicals supplied to the pulp mill in order to produce 0.9 million metric tonnes of ECF pulp (tonnes bleaching chemicals/ 0.9 Mtonnes ECF pulp) which corresponds to the pulp mills annual production capacity. In Table *1* the bleaching chemicals supplied to the pulp mill are presented. The chlorine dioxide solution produced from the different chlorine dioxide generators contains 9 -10 g ClO2 per litre and has a content of 0.2 g Cl2 per litre.

ECF bleaching chemicals supplied to pulp mill annually in metric tonnes for production of 0.9 million tonnes pulp	
Chlorine dioxide,ClO_2	13 500
Hydrogen Peroxide, H_2O_2	3 600
Sodium Hydroxide, NaOH	16 200
Sulfuric acid, H_2SO_4	19 000
Sodium Sulfate, $NaSO_4$	14 850
Sodium Chlorate (export)	

Table *1. Bleaching chemicals annually supplied to the pulp mill plus export of sodium chlorate to the open market.*

3.2.4. System boundaries

The eco-efficiency assessment will cover the production of bleaching chemicals from cradle to delivery of the chemicals at the pulp mill, a cradle-to-gate study. The extraction process of resources and the processing and manufacturing of chemicals used as input to the production process will be covered in the study. The transportations of chemicals from the extraction point to refinement and finally to the chemical production site will all be included within the system boundaries.

The entire cradle-to-gate system is divided into a foreground and a background system. The foreground system includes the production of bleaching chemicals performed by Eka Chemicals. The system is in direct influence by decisions made at Eka Chemicals. The background system is defined as the system Eka Chemicals does not control and in which the foreground system is located and interacts with. The system boundaries are presented in Figure 1. The system boundaries and the definition of background/foreground system are described in the chapter Base case scenario.

The Life Cycle Costing (LCC) is defined to be actor-specific. The scope of the cost calculation follows the goal and scope of the LCA (Borén, 2008). Since the study is defined as a cradle-to-gate study the cost calculations will be investigated from a producer’s perspective, in this study Eka Chemicals. Therefore the costs for producing bleaching chemicals will be considered. The LCC used in the case study is strictly related to the functional unit and intended to investigate the economic performance of the different production concepts.

There are several ways of producing the required bleaching chemicals needed for production of ECF pulp. However, the different production concepts compared on the basis of eco-efficiency in this study are as followed the SVP-SCW, the SVP-LITE, the chemical island and the integrated plant. SVP-SCW and SVP-LITE are two stand-alone chlorine dioxide generators producing chlorine dioxide using methanol as reducing agent. The chemical island concept includes a chlorate plant combined with a chlorine dioxide generator also using methanol as reducing agent. The integrated plant process uses an SVP Total-HCl, which is an integrated chlorine dioxide generator, using a chloride based process instead of methanol. The different production concepts are presented in the chapter Concepts included in the Eco-efficiency assessment. The different process concepts provide a mix of various amounts of bleaching chemicals. Some chemicals are not produced on-site and therefore not included in the production processes. Those chemicals are instead supplied directly to the pulp mill.

The assessment will be based on a default scenario where the production facility is situated in Russia. The background system is modeled to represent an average situation in Russia.

The default scenario will be implemented into other geographic locations where production of bleaching chemicals may be of interest for Eka Chemicals. The regions investigated are China, Indonesia, Australia and Brazil. The default scenario will also be implemented into a background system where the electricity used on-site is assumed to be produced from biomass in pulp mill. The eco-efficiency assessment of the default scenario in Russia will be conducted comparing the different production concepts in the foreground system and the background system will stay static. However, when comparing different geographical scenarios the foreground system is set to be static and the background system will be adapted in order to represent the properties of the investigated region.

The production processes of bleaching chemicals used for ECF pulp production does not only differ between different concepts and countries. Instead every production concept is uniquely designed in order to satisfy the demand for each and every pulp mill. In order to make the Eco-efficiency assessment useful for Eka Chemicals, the model developed can be used evaluating different types of pulp mills, constellations and scenarios.

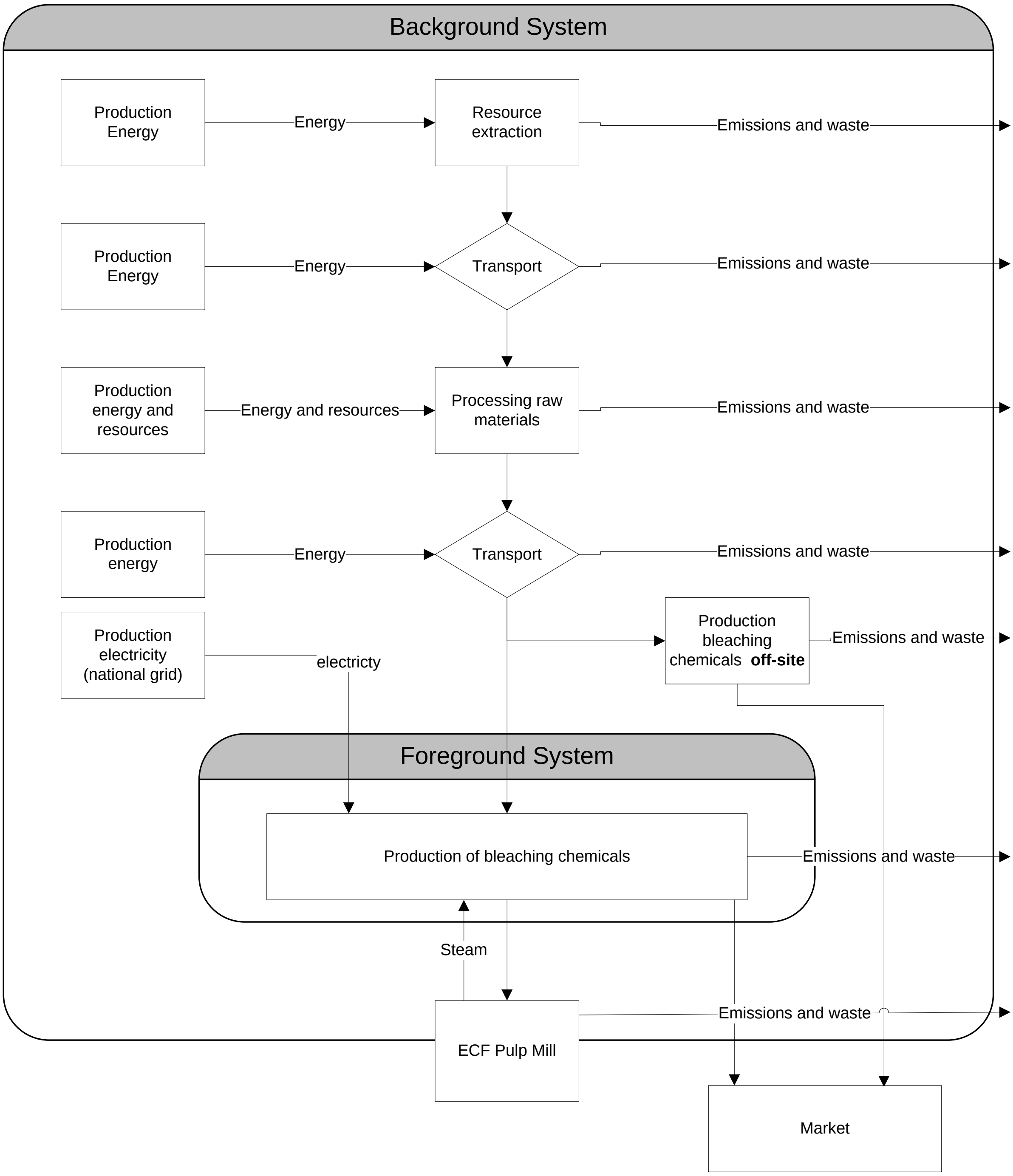

Figure 1 *System boundaries of the Eco-efficiency assessment, cradle-to-gate. The figure defines the foreground and background system.*

3.2.5. Data requirements

The data regarding the bleaching chemicals production processes used in the Eco-efficiency assessment, the foreground system, will be collected at Eka Chemicals via interviews. The aim is to collect data as representative as possible for the Russian ECF pulp industry. When primary data, site specific data, is accessible it will be used. However, secondary data, average data, will also be useful e.g. for raw materials. For data collection, regarding the background system, existing LCA studies will be used as references. Data will also be collected from different generic LCA data bases.

The data representing the background system is based on secondary data, data with average properties. This is the case since primary data according to the specific sites are not available. Including primary data, the effect on the margin, is therefore not possible. The time frame of this study doesn´t allows the possibility of investigating and including primary data for the background system.

3.2.6. Impact categories

The Life Cycle Impact Assessment (LCIA) aims at describing the environmental consequences of the environmental impact quantified in the Life Cycle Inventory (LCI). In the LCIA the results from the LCI is classified into different impact categories according to LCA standards in order to investigate the environmental impact. (Baumann & Tillman, 2004) The LCIA will be carried out according to the BASF eco-efficiency methodology (Saling, 2002). There are six impact categories according to eco-efficiency assessment methodology. However, only four will be covered in this case study. These are resource consumption, energy consumption, emissions and land use. The eco-efficiency assessment performed in 2008 concluded that the contribution to the impact categories toxicity potential and risk potential did not vary significantly between the different concepts compared. Further on, the toxicity potential and the risk potential contributed little to the total environmental impact. On this basis, the impact categories toxicity and risk potential will not be covered in the study.

3.2.7. Classification and Weighting methods

The weighting of an eco-efficiency assessment transforms multiple inventory data into one single index. The index represents the total environmental impact caused by the system. Since the LCI often provides multiple data covering different environmental areas, the classification converts complex data into different impact categories. The result becomes more interpretable for the receiver since he or she does not have to study the results in detail to understand the outcome of the study. Further on, the intended audience do not need to be specialists within environmental issues in order to understand and interpret the LCA. However, eco-efficiency assessment methodology requires the LCI result to be weighted and converted into one final index representing the total environmental load the system creates. Moreover the LCC may result in an index representing the financial impact performance of the investigated system. The environmental and economic indices are finally normalized into an eco-efficiency standard according to the BASF eco-efficiency method (Saling, 2002).

3.3. Base case scenario

This chapter aims at describing the system which represents the base case scenario in the eco-efficiency assessment. The base case will be used as a reference when comparing the eco-efficiency of the different production concepts for bleaching chemicals to the ECF pulp industry. It will also be used in order to compare other scenarios both considering changes in the background system as well as changes in the foreground system. Firstly the background system is defined and explained. It includes the demand for bleaching chemicals by the pulp mill, the geographic location of the pulp mill and the electricity and energy system with which the pulp mill interacts. Producing and transporting raw materials consumed in the production of bleaching chemicals are also a part of the background system. Secondly, the foreground system will be explained. Since the four production concepts are independent systems the SVP-SCW and the SVP-LITE will firstly be defined and explained followed by the chemical island and finally the integrated plant.

3.3.1. Background system

The pulp mill requiring the bleaching chemicals for its production is situated in Russia. The annual production of ECF pulp is 0.9 million tonnes. In order to annually produce the pulp 13 500 tonnes of chlorine dioxide, 3 600 tonnes of hydrogen peroxide, 16 200 tonnes of sodium hydroxide, 14 850 tonnes of sodium sulfate and 19 000 tonnes of sulfuric acid have to be delivered to the pulp mill. The chlorine dioxide solution delivered to the pulp mill contains 9-10 g ClO_2 per liter with a chlorine content of 0.2 g per liter. The mill is producing pulp 350 days per year and running 24 hour per day.

The energy (steam) used in the on-site production of bleaching chemicals is assumed to be produced at and delivered by the pulp mill. A pulp mill mainly uses timber as primary energy carrier. Since the pulp mill produces a net surplus of steam the energy is assumed to be produced from biomass.

The sodium sulfate generated from the production concepts is delivered to the pulp mill. The need for sodium sulfate is different for different pulp mills. It is assumed that the need for sodium sulfate at the pulp mill is covered by the amount produced on-site, representative for Russian pulp production. Therefore sodium sulfate is neither purchased from external sources nor regarded as waste.

Sodium chlorate is produced on-site for the systems with chemical island and integrated plant. The chlorate is used internally on-site as a feed-stock for chlorine dioxide production. However, the external market demand for sodium chlorate in the region around the plant is also considered. The chlorate plant on the chemical island is dimensioned in order to also generate the extra amount of chlorate for the market demand. For the systems with stand-alone chlorine dioxide generators and integrated plant the market demand of sodium chlorate is assumed to be covered by external suppliers.

Hydrogen is generated on-site for systems with chemical island and integrated plant. The hydrogen is used by the pulp mill as fuel in its lime kiln. Usually, natural gas is used for covering the energy demand in this specific process. Therefore, the net consumption of natural gas is assumed to be decreased if hydrogen produced on-site replaces natural gas as energy carrier in the lime kiln. The systems generating hydrogen used as fuel on-site is given a credit for replacing natural gas.

The external suppliers of bleaching chemicals and raw materials are producers assumed to be located in different geographic locations. The base case suppliers are defined in Table 2 where the production location is specified. When bleaching chemicals are directly supplied from external sources to the pulp mill and when the raw material for the production of bleaching chemicals is purchased externally it is assumed those products origin from suppliers located according to Table 2.

Bleaching Chemicals and raw materials	Supplier	Location of producer	Transportation
Sodium chlorate	Eka	Alby and Oulu	lorry to Finland, train from Finland
Sodium hydroxide		Domestic Russia	Train
Hydrogen peroxide		Domestic Russia	Train
Sodium sulfate		Domestic Russia	Train
Sulfuric acid		Domestic Russia	Train
Raw material			
Water	Pulp mill		Pipeline
Sodium chloride		Domestic Russia	Train
Methanol		Domestic Russia	Train
Sodium dichromate		Domestic Russia	Train

Table 2 Supply of chemicals from off-site production.

Sodium chlorate is, if no chlorate plant is included in the concept, assumed to be produced in Alby in Sweden and in Oulu in Finland. It is assumed that fifty per cent of the sodium chlorate is produced in Alby and fifty per cent in Oulu. The sodium chlorate is transported by lorry and ferry from Alby to Finland and continuing to Russia by train. Sodium chlorate produced in Oulu is transported by train to Russia.

The bleaching chemicals externally supplied to the pulp mill and the raw materials produced in Russia are assumed to be produced within a 1000 km radius from the pulp mill. Those products are transported by train to the pulp mill.

The water used as raw material and energy carrier on-site is assumed to be extracted from near-by lakes and rivers in Russia. It is delivered via pipelines to the site.

3.3.2. Foreground System

3.3.2.1. SVP-SCW and SVP-LITE

The SVP-SCW and the SVP-LITE are stand-alone chlorine dioxide generators producing chlorine dioxide and sodium sulfate which are supplied to the pulp mill. Their respective capacities are dimensioned to satisfy the demand of chlorine dioxide of the pulp mill in Russia in order to produce its annual tonnage of pulp. Since the stand-alone chlorine dioxide generators do not produce a complete mix of bleaching chemicals needed for ECF pulp production the missing chemicals are instead purchased and delivered from external sources. Those bleaching chemicals are produced and delivered according to the base case background system and Table 2. Likewise, the raw materials consumed in the SVP-SCW and the SVP-LITE processes supplied by the producers defined in the base case background system. Figure 2 shows the system with SVP-SCW and SVP-LITE defined as foreground system in the background system.

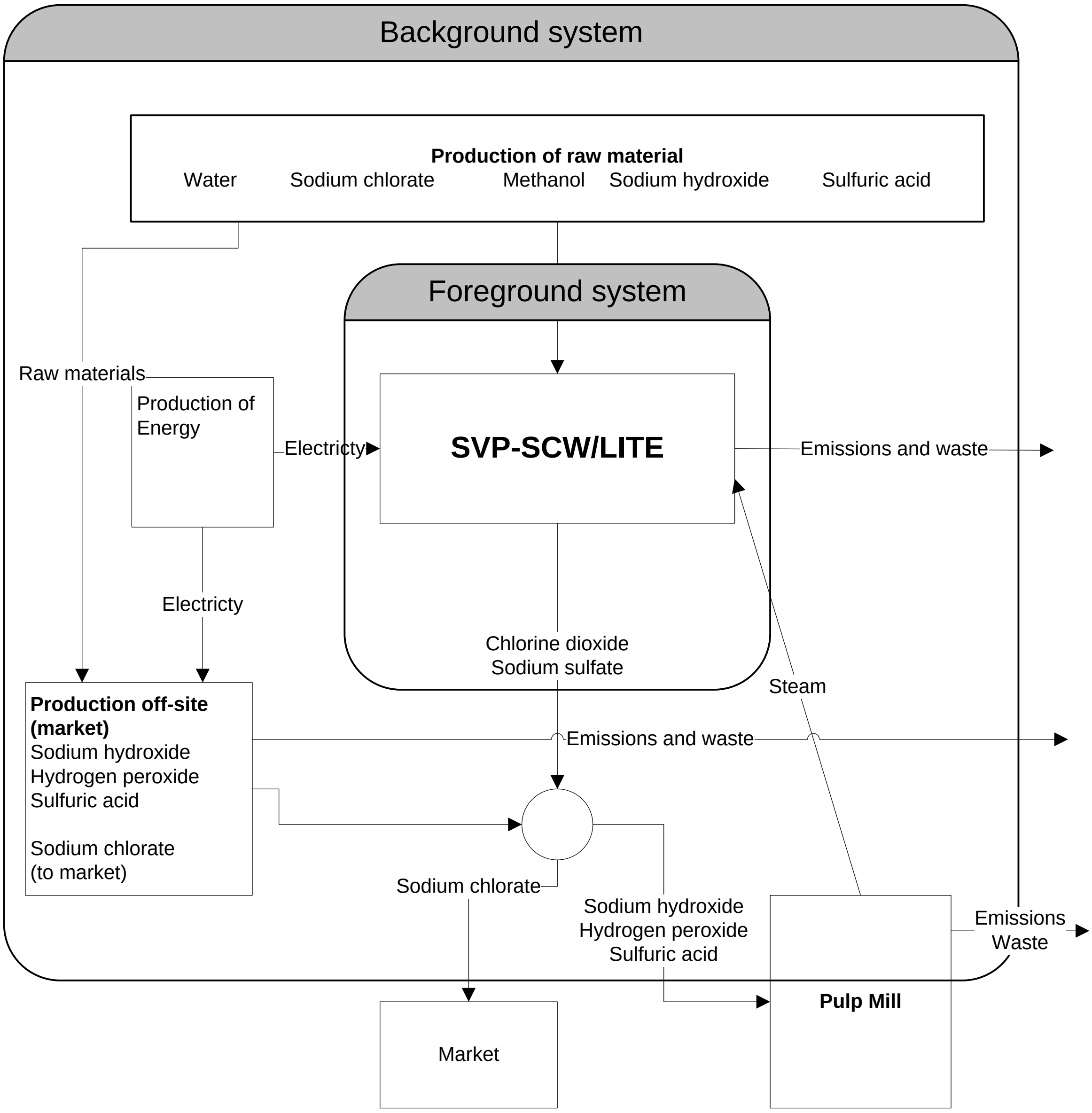

Figure 2 The stand-alone chlorine dioxide generator foreground and background system.

3.3.2.2. Chemical Island

The system with chemical island consists of one sodium chlorate production unit and one chlorine dioxide generator. The chlorine dioxide generator is a SVP-SCW which makes it possible to both deliver sodium sulfate to the pulp mill and produce sodium sulfate for storage and possible export. The chlorine dioxide generator is dimensioned for producing the amount of chlorine dioxide required to produce the annual tonnage of ECF pulp. There is no excess of sodium sulfate in the studied case.

The sodium chlorate plant is dimensioned to supply chlorate for both the chlorine dioxide production and for export. The hydrogen generated in the chlorate plant is supplied to the pulp mill and is used as energy in the lime kiln.

The chemicals hydrogen peroxide, sodium hydroxide and sulfuric acid are supplied to the pulp mill from external suppliers according to Table 2 and the base case background system. Likewise, the raw materials to the chemical island are supplied by external suppliers. In Figure 3 the system boundaries for the chemical island are shown including the division into foreground and background systems.

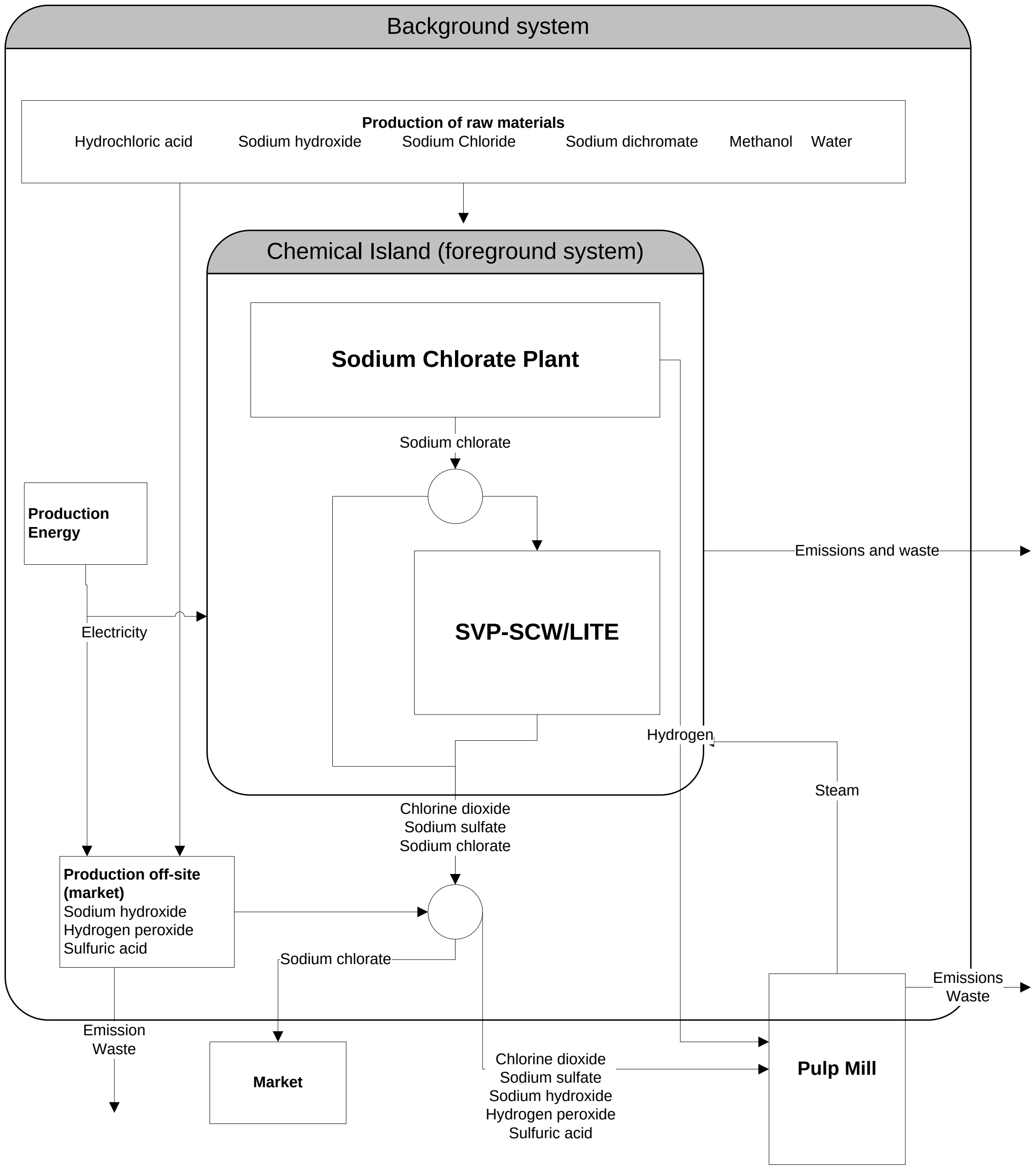

Figure 3 The chemical Island foreground and background systems

3.3.2.3. Integrated Plant

The Integrated plant investigated consists of four different units; the chlorine dioxide generator, the sodium chlorate plant, the chlorine alkali plant and the hydrochloric acid burner. Since the processes are interconnected to each other the dimensions of the different units depend on each other. In the base case scenario the chlorine alkali process is designed to produce the required amount of chlorine for the hydrochloric acid burner. The hydrochloric acid burner on the other hand produces the needed required amount of hydrochloric acid used in the chlorine dioxide generator. The chlorine dioxide generator is further dimensioned to satisfy the demand for chlorine dioxide consumed when producing ECF pulp. Finally, the capacity of the sodium chlorate plant is set equal to the required amount of sodium chlorate for the chlorine dioxide production. The market demand is assumed to be produced in Alby and Oulu and delivered to the pulp mill site according to defined background system and Table 2.

The hydrogen generated in the processes is used as fuel in the lime kiln at the pulp mill. Most of the hydrogen is generated in the chlorine alkali plant and the sodium chlorate plant.

Since the chlorine alkali process is dimensioned to generate chlorine to the hydrochloric acid burner, the sodium hydroxide demand at the pulp mill cannot be satisfied by the on-site production. The deficit of sodium hydroxide is imported and is supplied from the base case background system. Further on, are the hydrogen peroxide and the raw materials used on-site purchased from the suppliers in the background system, defined in Table 2.

The chlorine dioxide generation for the system with integrated plant is a chloride based process, the SVP-Total HCl. This process generates no sodium sulfate. Since the pulp mill requires sodium sulfate for the pulp production process it is supplied to the pulp mill from external sources and produced according to the background system and Table 2. The system with integrated plant is shown in Figure 4 including the division between foreground and background system.

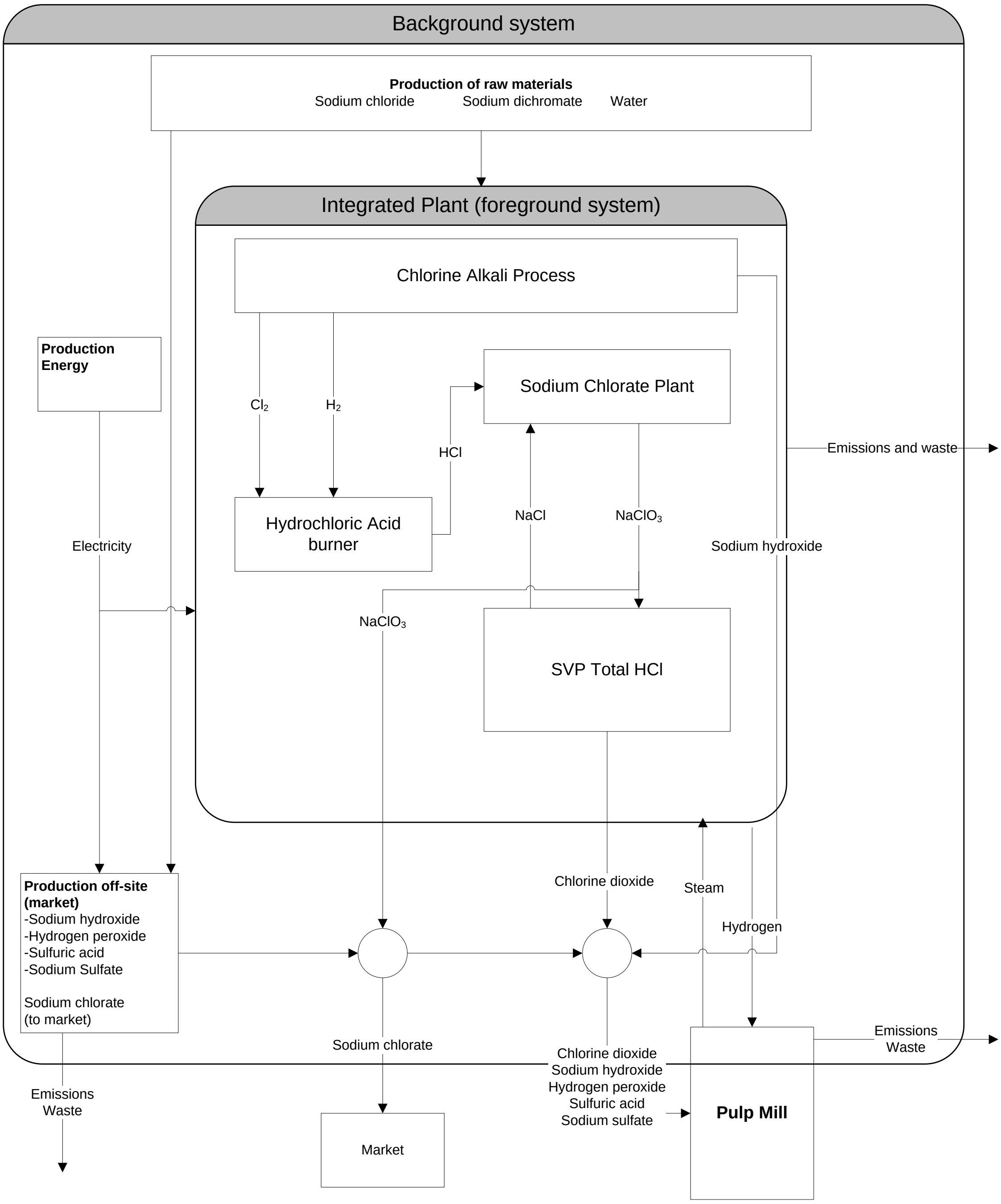

Figure 4 The integrated plant foreground and background systems

3.4. Scenario analysis

3.4.1. Scenario definition – Background system

3.4.1.1. Biomass scenario

Pulp mills usually generate a large surplus of energy. Waste-heat can therefore be supplied to surrounding industries or district heating networks. This is assumed to be the case in the base case scenario where the steam consumption on-site is covered by waste-heat from the pulp mill. It is further possible and common practice to generate electricity utilizing the surplus of steam in a steam turbine. The electricity can be delivered to the national grid or used on-site.

It seems reasonable to believe that utilizing electricity generated in the pulp mill should be beneficial to the environment. The primary energy carrier used in pulp mills are residuals from the pulp production and is therefore classified as renewable. Using electricity generated in the pulp mill for production of bleaching chemicals on-site therefore means production based on renewable energy, with no or low net carbon dioxide emissions.

The biomass scenario is based on the assumption that the electricity from the national grid, used in the production processes in the foreground system, is replaced by electricity generated in the pulp mill by biomass. It is the electricity used in the production of bleaching chemicals on-site which is replaced. The supply of bleaching chemicals and raw materials from the background system is not affected and are assumed to have the properties defined in the base case scenario. The system boundaries are visualized in Figure 5.

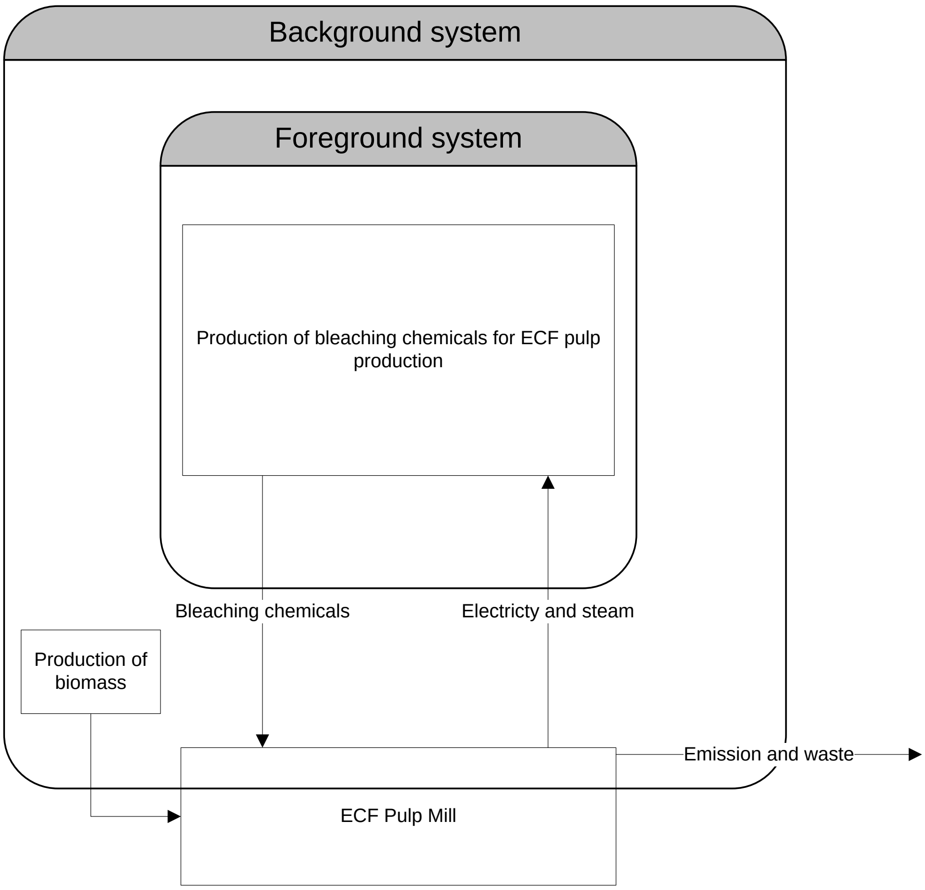

Figure 5 System boundaries in the biomass scenario

3.4.1.2. Electricity Scenarios

The properties of the electricity system are dependent on the infrastructure in the country or region where it is situated. The system is often developed during a long time of period and is usually influenced and characterized by the geographical properties, e.g. natural resources and political leadership in the region. Since the power plants and the distribution system, defining partly the electricity system, usually are operated for decades before being replaced, it is regarded as being inflexible.

The production processes used for ECF bleaching chemicals production are energy intensive, both with regard to steam and electricity consumption. Steam is generally produced and delivered by the pulp mill since its processes generate a surplus of the energy. It is therefore generated from biomass since wood is used as energy carrier in pulp mills. The electricity consumed when producing bleaching chemicals for ECF pulp production is in the base case scenario assumed to be generated by the Russian national grid.

The four production concepts investigated in the base case scenario, consume different amounts of electricity. Earlier studies show that the generation of electricity is a key parameter for the environmental impact caused by energy intensive processes or products. An earlier eco-efficiency assessment performed by the Sustainable Development Group at AkzoNobel highlighted the importance of the properties of the background electricity system in order to decide the eco-efficiency of production processes for pulp bleaching chemicals (Halldén, 2010). Further on one of the purposes of this study is to investigate the eco-efficiency of different production concepts and conclude to what extent the geographical location of the production affects the eco-efficiency. Therefore the four production concepts will be compared in terms of eco-efficiency using four different background electricity scenarios. The electricity scenarios are chosen in order to represent possible geographical locations for ECF pulp production worldwide. The electricity systems included are the Brazilian, the Indonesian, the Chinese and the Australian. The four production concepts will be compared to each other with regard to eco-efficiency utilizing one of the four electricity systems at a time. One scenario for each country mix will be created and assessed.

The properties of the national electricity systems are based on data from 2007 collected by the International Energy Agency (IEA). The data covers the domestic generation of electricity in each country during 2007. In Table 3 the total amount of electricity generated in 2007 for the current countries are presented, together with the share of the total production and source. The shares of electricity produced from fossil and renewable resources are presented. The electricity generation in Russia, Indonesia, China and Australia is mainly produced using non renewable energy resources. In Brazil on the other hand 88 per cent of domestic electricity generation in based on hydro power.

	Russia	**Brazil**	**China**	**Indonesia**	**Australia**
Coal	17%	2%	81%	45%	76%
Oil	2%	3%	1%	27%	1%
Gas	48%	3%	1%	16%	15%
Biomass	0%	4%	0%	0%	1%
Nuclear	16%	3%	2%	0%	0%
Hydro	18%	84%	15%	8%	6%
Geothermal	0%	0%	0%	5%	0%
Wind	0%	0%	0%	0%	1%
Fossil	82%	12%	85%	87%	92%
Renewable	18%	88%	15%	13%	8%
Total electricity generation [TWh]	1015.3	445.1	3279.2	142.2	255.0

Table 3 *Electricity generation data published by IEA (2007), in percentage of the total electricity generation and divided into source of energy (non renewable or renewable)*

The system affected by the different electricity scenarios is the foreground system. It is the electricity consumed on-site when producing bleaching chemicals for ECF pulp production that is replaced in the four electricity scenarios. The external supply of bleaching chemicals and raw materials to the pulp mill and the production process of bleaching chemicals are identical to those in the base case scenario. Likewise, the transportation distances are not changed since it is assumed that the bleaching chemicals produced externally are purchased from the local market. It is characterized according to Table 2 independently of the geographical location.

3.4.1.3. Transportation Scenario

The transportation distances and the properties of the transports in the base case scenario are relevant for Russia. Russia is large country with infrastructure much dependent on railways. Thus, assuming domestic transportation distances of 1000 kilometres by train seemed reasonable. However, in order to investigate if and how the properties of the transportations affect the eco-efficiency of the four concepts investigated was a new scenario created. The idea is to investigate if the geographic location of the production site affects the eco-efficiency of the four production concepts with regard to transportations.

Based on conversations with Björkman (2010) the distance of the transportations in this scenario is defined to 300 kilometres. Further on, the raw materials and the bleaching chemicals are assumed to be transported by truck. The idea is to create a scenario which is a compromise when it comes to representing China, Brazil, Indonesia and Australia. It is however important to notice that the transportation distances and transportation type of sodium chlorate from Alby and Oulu not is changed in the transportation scenario as compared to the base case, even though these transports are considerably longer in these scenarios compared to the base case.

The transportation scenario is otherwise identical to the base case scenario. The demand for raw materials used in the production processes of bleaching chemicals and the external supply of these chemicals are not changed. The steam is produced on-site from biomass and the electricity consumed in the processes is generated in Russia.

3.4.2. Scenario definition - Foreground systems

3.4.2.1. Sodium Hydroxide Scenario

Sodium hydroxide is a basic chemical used when producing pulp, including production of ECF pulp (Smook, 2002). The amount of sodium hydroxide needed is, compared to the amount of other chemicals needed, substantial. For pulp production in Russia it is assumed 18 000 tonnes of sodium hydroxide are required in order to produce one million ton ECF pulp.

Sodium hydroxide is not produced on-site for the systems with SVP-SCW, SVP-LITE or chemical island. Those constellations include no sodium hydroxide generating processes and the chemical is instead supplied to the pulp mill from external producers. The system with integrated plant on the other hand generates sodium hydroxide together with chlorine and hydrogen in the chlorine alkali process. The chlorine alkali process can be dimensioned to cover the total demand of sodium hydroxide in the pulp mill. A larger chlorine alkali plant will generate an extra amount of chlorine. The system will therefore produce a surplus of chlorine which must be taken care of. The chlorine might be used for chlorine production, for hydrochloric acid production or used in order to produce Poly-Aluminum Chloride (PAC). The chlorine and the hydrochloric acid might be exported and PAC is sometimes attractive to use on-site.

In order to investigate if it is eco-efficient to build a integrated plant dimensioned in order to produce the entire amount of sodium hydroxide required on-site a what -if scenario is created. The systems with SVP-SCW, SVP-LITE and chemical island are the same as in the base case scenario. However, the system with integrated plant is dimensioned to cover the entire annual pulp mill demand for sodium hydroxide. Thus, there is no need for supplying sodium hydroxide from the market. The surplus of chlorine is assumed to be sold-sold off to the market and a credit for this production is gained. The properties of the credit is representing production of chlorine using the chlorine alkali-process used on-site and applying mass allocation between sodium hydroxide and chlorine. The extra amount of hydrogen generated in the process is used as energy in the lime-kiln.

Sodium hydroxide scenario	Produced on-site IP	Used in IP	Pulp mill demand	Delivered to market
Sodium hydroxide	16 200 tonnes		16 200 tonnes	
Chlorine	14 200 tonnes	10 500 tonnes		3 700 tonnes

Table 4 Material balance for IP production of sodium hydroxide and chlorine in the sodium hydroxide scenario

3.4.2.2. No export of sodium chlorate scenario

Installing a system with chemical island and integrated plant includes the opportunity of installing a chlorate plant which can be designed in order to generate enough sodium chlorate to cover both the on-site demand and the market demand. This is the case in the base case scenario where sodium chlorate is exported to off-site consumers for the chemical island system. Sometimes, the demand for sodium chlorate is low near the current pulp production site. The reason can be that there are already producers of sodium chlorate in the region. Or the infrastructure can be limited and thus it will be expensive or difficult to export sodium chlorate.

An additional scenario is constructed in order to rank the four production concepts with regard to eco-efficiency when no export of sodium chlorate is needed. The scenario is assumed to have the properties of the base case scenario, except that the chlorate plant installed for the chemical island system is designed in order to only satisfy the demand for sodium chlorate on-site. The extra amount of sodium chlorate for export is not included in this scenario as for the base case. For SVP-SCW, SVP-LITE and integrated plant, there is no need to produce sodium chlorate externally to satisfy the market demand assumed in the base case scenario.

3.4.2.3. No supply of sodium sulfate scenario

Sodium sulfate is generated as a by-product when producing chlorine dioxide for systems with SVP-SCW, SVP-LITE and chemical island. The properties of the sodium sulfate differs between the different concepts, however, the chemical is attractive and is used by the pulp mill as a source of sulfur for its processes.

The demand for sodium sulfate differs between different pulp mills. In some regions the demand is large while in others there is no need for the chemical. Sodium sulfate is in the base case scenario a chemical the pulp mill in Russia demands. In order to investigate if and how the demand for sodium sulfate affects the overall eco-efficiency of the four production concepts a sodium sulfate scenario is created.

In this scenario it is assumed that there is no demand for sodium sulfate from the pulp mill. The system with integrated plant generates no sodium sulfate when producing chlorine dioxide. The need for delivering sodium sulfate from external sources to the pulp mill with integrated plant, as in the base case scenario, is therefore not there anymore. However, the systems with SVP-SCW, SVP-LITE and chemical island generate sodium sulfate whether or not it is requested. It is assumed in this scenario that there is no market demand for the sodium sulfate. The generated sodium sulfate is therefore assumed to be landfilled at the pulp mill.

3.5. The cost aspect

The cost aspect is central in an eco-efficiency study. The cost representing the studied alternative should be calculated using the system boundaries defined in the goal and scope. The system boundaries in this study are set to go from cradle-to-gate, accordingly the production cost from Eka should be used. I have performed an extensive cost estimate and those costs are included in the eco-efficiency results of this report. Further on, the income from selling the produced chemicals has been calculated. However, Eka does not allow me to present actual costs in this report, the public report, since those are strategically important. Nevertheless, below follows a description on how the costs have been calculated in this study.

The costs are calculated on the basis of investment cost, raw material costs and the cost for purchasing energy. For the systems with CI and IP, where hydrogen is generated, an economic credit is given based on the price for replacing natural gas.

However, the cost for producing chemicals for the base case scenario, the sodium hydroxide scenario and the no sodium chlorate scenario varies due to varied investment cost and due to different sets of chemicals produced. In order to compare the production concepts included in the study and the differences in the three scenarios the cost for producing the chemicals, the income on selling the chemicals and the resulting profit has been calculated. The price the pulp mill pays for the bleaching chemicals subtracted by the production cost is defined in this report as the profit.

$$\mathrm{Pr}\mathit{ofit} = \mathrm{Pr}\mathit{ice\_of\_bleaching\_chemicals\_pulp\_mill} - \mathrm{Pr}\mathit{oduction\_}\mathrm{cos}\mathit{t}$$

The income on selling the bleaching chemicals is calculated through using current market prices. Chemicals purchased from external suppliers are assumed to be zero revenue chemicals. The costs for Eka Chemicals of delivering the chemicals are equal to the price the pulp mill pays for the chemicals.

The possible profit the production concepts might generate is the difference between the fixed and variable annual cost and the income on selling the products produced. Income for the systems with CI and IP are also affected by the amount of hydrogen which can be utilized as energy in the pulp mill as well as income on producing and exporting chemicals to the market.

The system with IP is divided into two different units. The sodium chlorate plant, the chlorine dioxide generator and the hydrochloric acid burner is regarded as one unit. The chlorine alkali process is regarded as the other unit. The division is partly done due to the possibility of increasing the capacity of the chlorine alkali process without affecting the other processes material balances and partly due to that there is no need to split the sodium chlorate plant, the chlorine dioxide generator and the hydrochloric acid burner since their material balance is regarded as one. Therefore the need for varying the production size of the sodium chlorate plant is unnecessary.

The possible income on selling the excess of chlorine generated in the system with IP in the sodium hydroxide scenario is included in the calculations.

Prices on raw materials, energy and bleaching chemicals are collected from Eka and represent current market prices in Russia.

The costs for producing bleaching chemicals are different in the base case, the sodium hydroxide scenario and the no sodium chlorate scenario. This is the case since the investment and variable costs are changed when the material balances is changed between those scenarios. For the remaining scenarios the base case cost has been used.

3.6. Results

In this chapter, the results from the Eco-efficiency assessment case study are presented and discussed. The comparison of the alternative four production concepts has been carried out for 9 different scenarios with varying assumptions. The scenarios and assumptions are described in detail in the chapter Scenario analysis. A summary of the scenarios and assumptions is presented in Table 5. The assumptions are related either to the foreground system (processes in control of Eka Chemicals or the Eka value chain) or the background system (e.g. the infrastructure for producing and supplying electricity via the national grid and transportation infrastructure). Thus, the results of the assessed scenarios are sorted between foreground system results and background system results to make the interpretation easier and more transparent. This way the case study results will be more useful for decision making at Eka Chemicals.

Scenarios	**Most important changes in the assumptions compared to base case scenario**
Background system	
Biomass	Electricity consumed on-site is produced from biomass in pulp mill.
Brazil	Brazilian electricity mix
Australia	Australian electricity mix
China	Chinese electricity mix
Indonesia	Indonesian electricity mix
Transportation	The transportations are performed by truck and the distance is set to 300km
Foreground system	
Sodium hydroxide	The demand for sodium hydroxide is produced on-site for the integrated plant. Excess of Chlorine.
No export of Sodium Chlorate	No market demand for sodium chlorate
No supply of Sodium Sulfate	Sodium Sulfate is not wanted by the pulp mill and is instead sent to landfill

Table 5 The most important differences between the base case and the other scenarios.

The eco-efficiency or EEA diagram (sometimes referred to as the eco-efficiency portfolio) is a tool to rank products or processes in terms of eco-efficiency. Sometimes it can be difficult to clearly rank the eco-efficiency of different products, e.g. when the balls in the diagram are very close to each other. Further on the EEA diagram does not point out any arguments for why the products are ranked in a certain way. In order to investigate the cause of a certain ranking and to discuss differences between the alternatives compared, the underlying results for environmental impacts and costs need to be examined.

For the base case scenario, the contributions to the total, weighted environmental impact made by the different environmental impact categories are presented in Table 6. The emissions have the largest relevance to the total weighted environmental impact caused by the production concepts investigated. Further on, the emissions to air have a significantly higher relevance to the impact category emissions than emissions to water and the generation of solid wastes. Land use has a low relevance to the total weighted environmental impact.

Impact Category	Relevance	Relevance
Resource Consumption	**35%**	
Energy Consumption	**20%**	
Emissions	**42%**	
Emissions to air		72%
Emissions to water		25%
Solid wastes		3%
Land Use	**3%**	
Sum	**100%**	100%

Table 6 The contributions made by the different impact categories to the total, weighted environmental impact for the base case scenario, 0,9 Mtonnes/year of bleached pulp in Russia.

The following assessment results will be presented for each scenario investigated:

- The eco-efficiency or EEA diagram
- Weighted and normalized total environmental impact
- Weighted natural resource consumption
- The total use of primary energy divided into renewable energy resources and non renewable energy resources
- Weighted and normalized impact from emissions to air (including acidification potential, AP, photochemical ozone creation potential, POCP, ozone depletion potential, ODP, and carbon footprint, GWP

3.6.1. Base Case Scenario

The result from the Eco-efficiency assessment in the base case scenario is shown in Figure 6. The four production concepts can be separated and ranked according to the environmental dimension using the EEA-diagram. The differences between the balls in the eco-efficiency diagram regarding the financial dimension are very small for the four concepts. Thus, it is not possible to rank the four production concepts based on their cost performance.

The SVP-SCW is the most eco-efficient of the four production concepts compared, closely followed by the SVP-LITE. The systems with IP and C.I. are less eco-efficient.

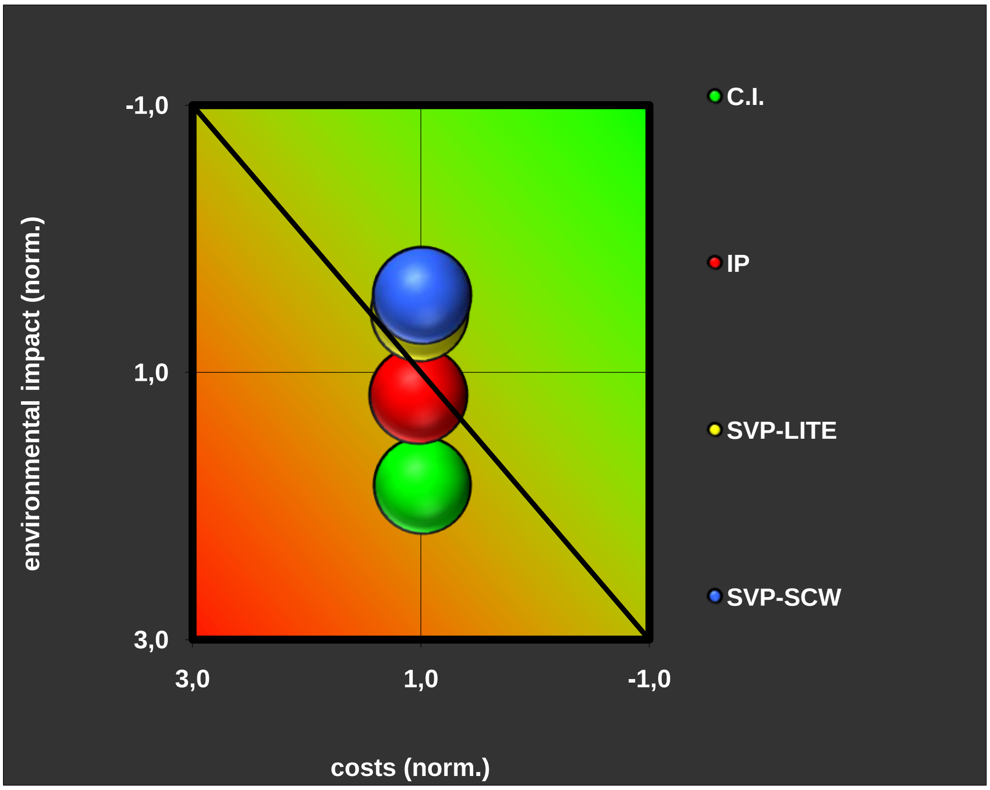

Figure 6. The EEA diagram, base case scenario

The total weighted and normalized environmental impact (according to the SD-method) is presented in Figure 7. The impact categories included are land use, emissions, energy consumption and resource consumption. The system with C.I. causes the largest environmental impact.

The results show that the significance of the four impact categories included is similar for the production concepts investigated. The generation of emissions is causing the highest contribution, followed by resource consumption, energy consumption and finally land use.

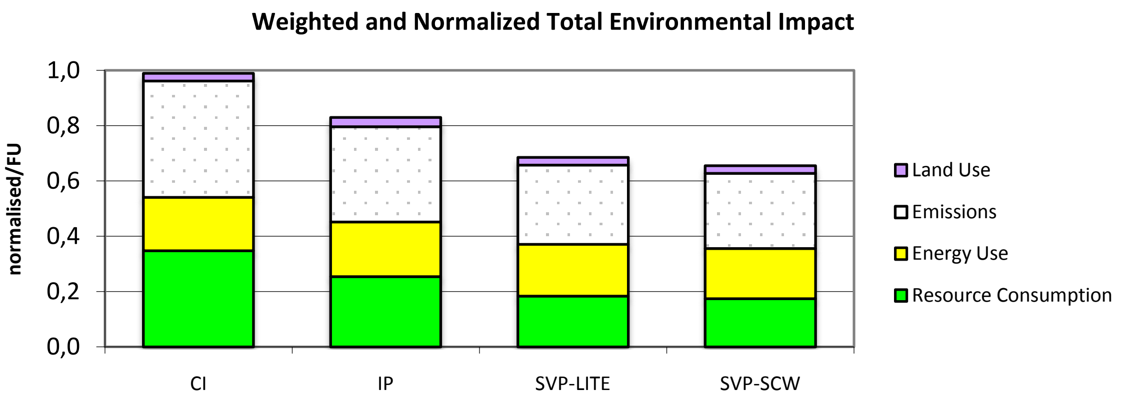

Figure 7 Weighted and normalized total environmental impact, base case scenario

Resource consumption results for the four production systems are presented in Figure 8. The largest contributions to the total weighted resource consumption when producing bleaching chemicals for production of ECF-pulp in the base case scenario are made by natural gas, crude oil, coal, lignite and barite (a mineral containing barium sulfate). The two alternative systems with chlorine dioxide generators are the most efficient ones in terms of consumption of natural resources. The system with C.I. has the highest total consumption of natural resources, twice as high as the SVP-SCW. The system with SVP-SCW scores best of the alternatives compared in terms of consumption of natural resources. The water consumption for the SVP-SCW is 88 per cent compared to IP which has the highest water consumption of the four production systems.

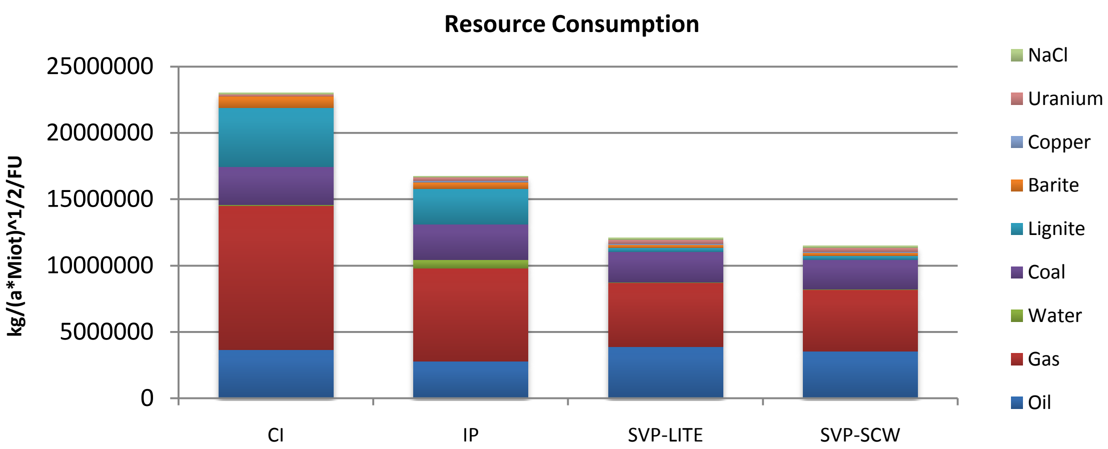

Figure 8 Total weighted resource consumption, base case scenario

The results for total primary energy use in the base case scenario are presented in Figure 9. The differences in primary energy use are not that big. The system with the IP requires the largest amount of primary energy. It consumes 4.5 PJ in order to provide the defined functional unit. Eight per cent of the total energy used origin from renewable energy sources. The C.I., the SVP-LITE and the SVP-SCW require 4.4, 4.2 and 4.1 PJ. The quote between renewable energy and non renewable energy is equal for the systems with IP, SVP-LITE and SVP-SCW. However, this quote is smaller for the system with C.I. which means that the share renewable energy sources are smallest for the system with C.I..

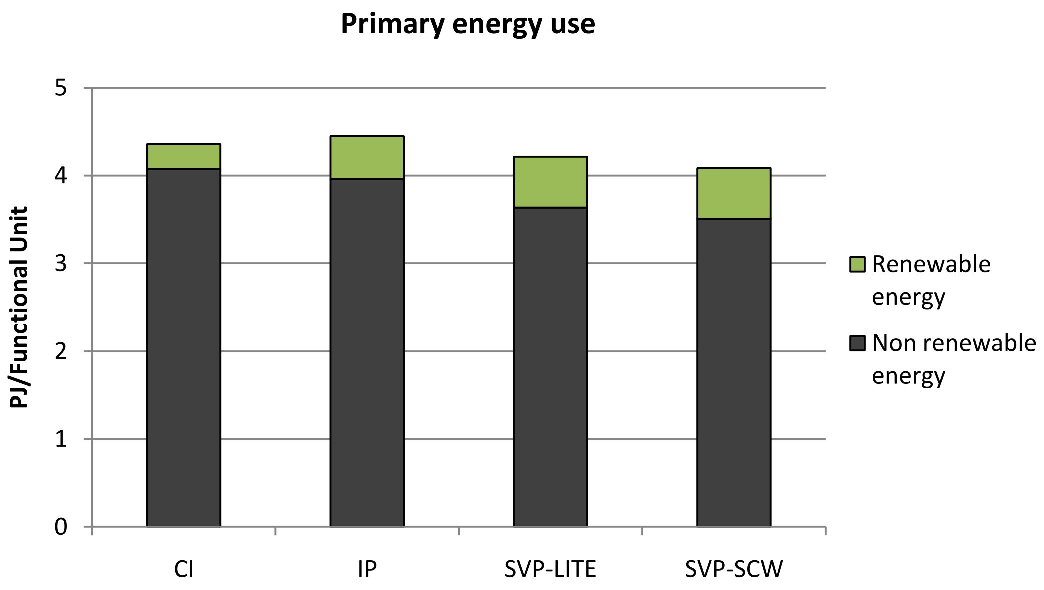

Figure 9 Total primary energy use, base case scenario

The results for weighted and normalized emissions to air are presented in Figure 10. The results show that the systems with SVP-LITE and SVP-SCW have the lowest environmental impact caused by emissions to air compared to the systems with C.I. and IP. The system with SVP-SCW has the lowest GWP of the four production concepts. Its carbon footprint (or global warming potential) is approximately half the carbon footprint of C.I. and 75 per cent of the carbon footprint of IP. The systems with SVP-LITE and SVP-SCCW contribute more to acidification (AP) and photo chemical ozone creation (POCP).

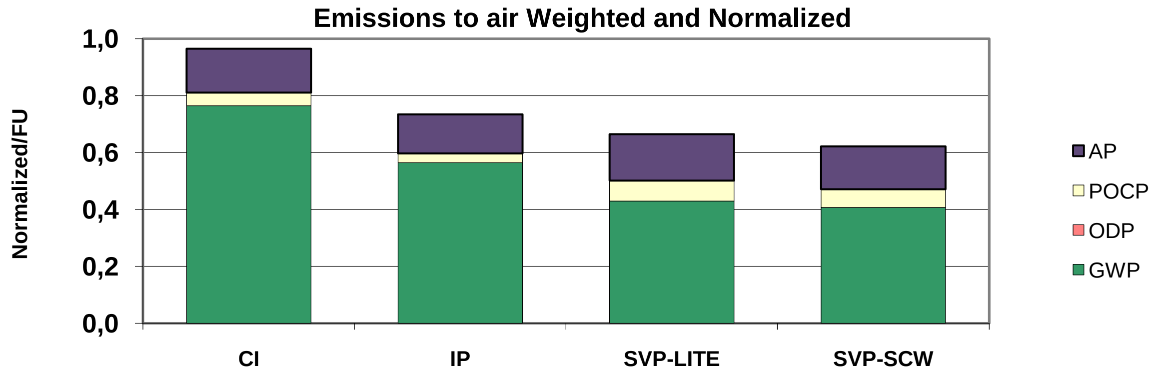

Figure 10. Weighted and normalized emissions to air, base case scenario. For each air emissions category (GWP, ODP, POCP and AP) the contributions are normalized towards the highest contribution included in the comparison. This is the explanation for C.I. not having a total weighed and normalized value for air emissions equal to 1.0 (C.I. is not the worst alternative for all air emission impact categories).

3.6.2. Background system

The results obtained when making the same comparison as in the base case but for scenarios with varying assumptions related to characteristics of the background system are presented.

in this chapter. The characteristics of the background system may be influenced but are not in direct control by Eka Chemicals control. The results presented in this chapter will however provide Eka personnel with knowledge regarding how characteristics of the background system affect the Eco-efficiency of the four alternative production concepts. This knowledge can be used for future strategic business decisions.

Assumptions and descriptions of the background scenarios can be found below in the sections electricity scenarios and transportation scenario. The most important differences in these scenarios compared to the base case scenario are summarized in Table 6.

3.6.3. Electricity Scenarios

The results from the biomass scenario are presented in this section. In this scenario it is assumed that the electricity required by stand alone chlorine dioxide generators, the chemical island and the integrated plant is generated by the pulp mill and based on biomass.

The other chosen and investigated electricity scenarios represent markets which are of interest for Eka Chemicals, now or within a near future. China, Indonesia, Australia and Brazil are all examples of such markets. Since China and Australia have similar production systems for electricity delivered from the national grid (Table 3), the Chinese scenario has been chosen to represent also Australia. Results from the Australian scenario will therefore not be presented in this report.

3.6.3.1. Biomass scenario

The results from the eco-efficiency assessment for the biomass scenario are presented in the EEA diagram, Figure 11. It shows that the system with C.I. is most eco-efficient. The results further indicate that the difference in eco-efficiency is not grand when comparing the systems with IP, SVP-LITE and SVP-SCW.

The ranking in terms of eco-efficiency in this scenario is reversed as compared to the base case scenario.

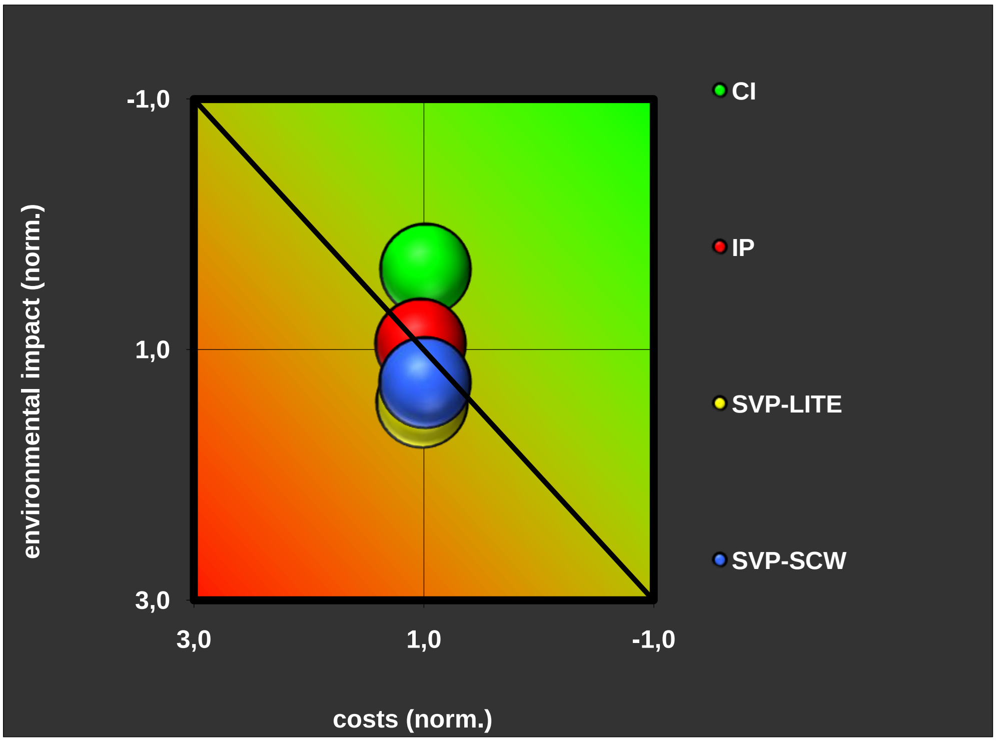

Figure 11 The EEA diagram for the biomass scenario

The results of the weighted and normalized total environmental impact are presented in Figure 12. It shows that the emissions contribute the most to the total environmental impact, disregarding studied production system. It further states that the resource consumption and the energy use are important impact categories for the systems with IP, SVP-LITE and SVP-SCW.

The system with the C.I. is the production system which causes the smallest environmental impact. Its impact is approximately 70 per cent of the impact made by the system with SVP-LITE. The differences between the systems with IP, SVP-LITE and SVP-SCW are smaller.

The land use for the C.I. system is of high relevance to the total environmental impact. The relevance is 14 per cent compared to 3 per cent in the base case. The relevance of land use is also increased for the IP system compared to the base case. This is due to that the electricity used on-site is generated from biomass. The relevance of land use is however not larger than emissions and energy use.

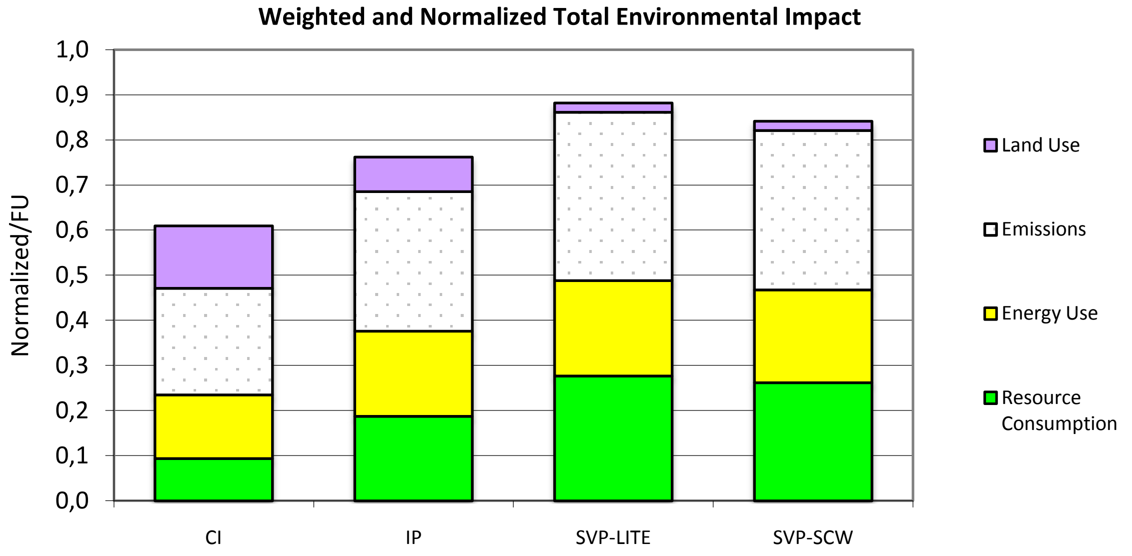

Figure 12 Weighted and normalized total environmental impact, biomass scenario

The weighted resource consumption for the biomass scenario is summarized in Figure 13. It shows that the C.I. system has a resource consumption being one third of the resource consumption of the system with SVP-LITE. The result further shows that oil is a central resource consumed by the C.I. system.

The systems with SVP-LITE and SVP-SCW consume the largest amount of natural resources, mostly oil, gas and coal. Similar results are presented for the system with IP. For the IP system, however, water and lignite are also significantly contributing to the total resource consumption.

The total weighted resource consumption is lower for all four production systems in this scenario as compared to the base case scenario. This is especially the case for the systems with C.I. and IP.

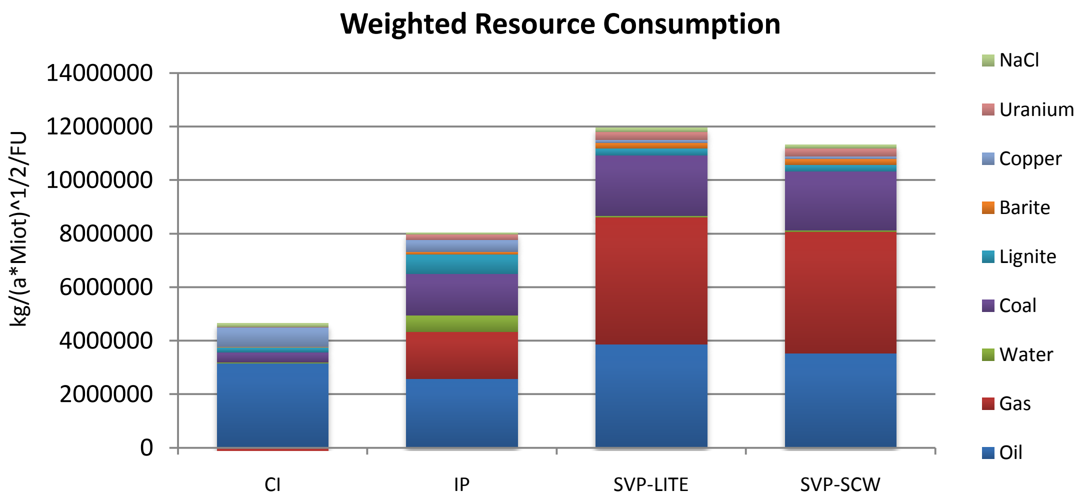

Figure 13 . Weighted resource consumption, biomass scenario.

The total primary energy use for the biomass scenario is presented in Figure 13. It shows that the system with C.I. uses the smallest amount of energy compared to the other production systems. Its energy use is 3.4 PJ and 79 per cent of that energy use origin from renewable energy resources. The system with IP uses 4.0 PJ and 39 per cent has its origin from renewable energy resources.

For the systems with IP and C.I., the primary energy use in the biomass scenario is lower as compared to the base case scenario. However the share of renewable energy resources is higher in this scenario. This is the case for the systems with stand-alone chlorine dioxide generators as well, however the difference is only a few percentage.

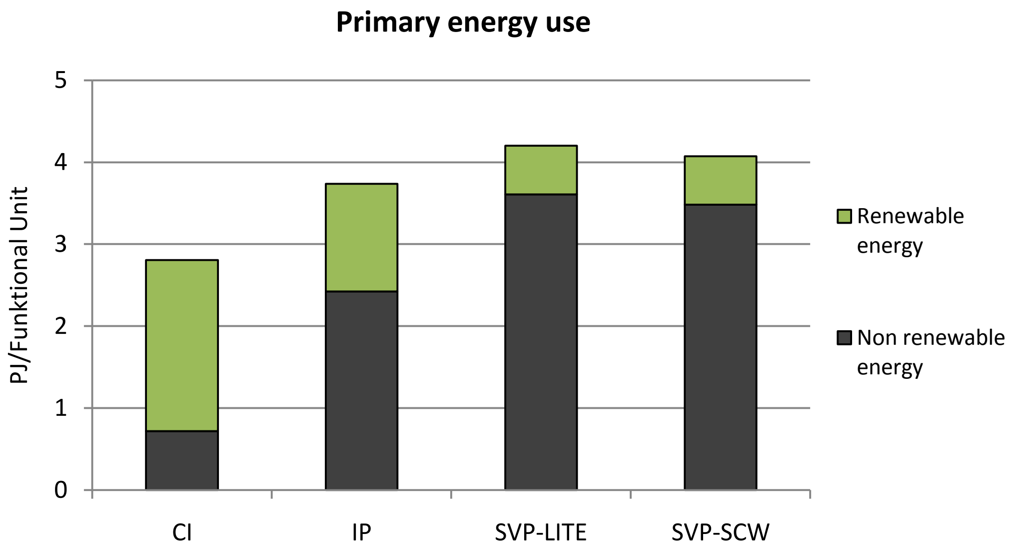

Figure 14 Total primary energy use, Biomass scenario

The results of the weighted and normalized air emissions are presented in Figure 15. The global warming potential, GWP, is the most relevant impact category for the four production systems regarding emissions to air. However, the GWP is considerably lower for the system with C.I. and IP as compared to the systems with SVP-LITE and SVP-SCW. This was not the case in the base case scenario.

The system with SVP-LITE has the highest contribution in this category of all the four systems studied.

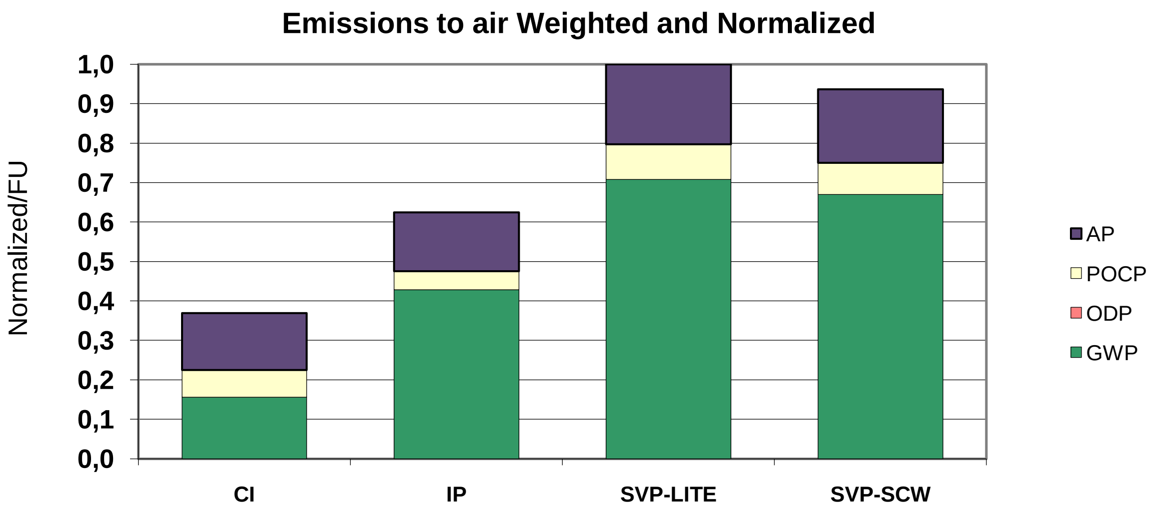

Figure 15 Weighted and normalized emissions to air, biomass scenario

3.6.3.2. Brazil

The contribution made by the different impact categories to the total, weighted environmental impact for the base case scenario was presented in Table 6. In the scenario representing Brazil this contribution is shifted and the result is presented in Table 7. The resource consumption is less relevant in this scenario compared to the base case scenario, while the energy consumption and emissions are more relevant. The emissions to air have a significantly higher relevance to the impact category emissions than emissions to water and the generation of solid waste. However, the relevance of water emissions is higher and the relevance of air emissions is lower in this scenario compared to the base case scenario.

Impact Category		Relevance	Relevance
Resource Consumption		31%	
Energy Consumption		23%	
Emissions		42%	
	Air Emissions		64%
	Water Emissions		32%
	Solid Wastes		4%
Land Use		4%	
Sum		100%	100%

Table 7 The contributions made by the different impact categories to the total, weighted environmental impact for the Brazilian electricity scenario.

The result from the electricity scenario representing Brazil is presented in the EEA diagram (Figure 16). It states the system with C.I. to be the most eco-efficient alternative compared to the three other production systems investigated. The system with IP is the second most eco-efficient alternative and the stand-alone chlorine dioxide generators are the least eco-efficient options. The systems with stand-alone chlorine dioxide generators are very close in eco-efficiency.

The ranking of the four production systems is completely reversed as compared to the base case scenario.

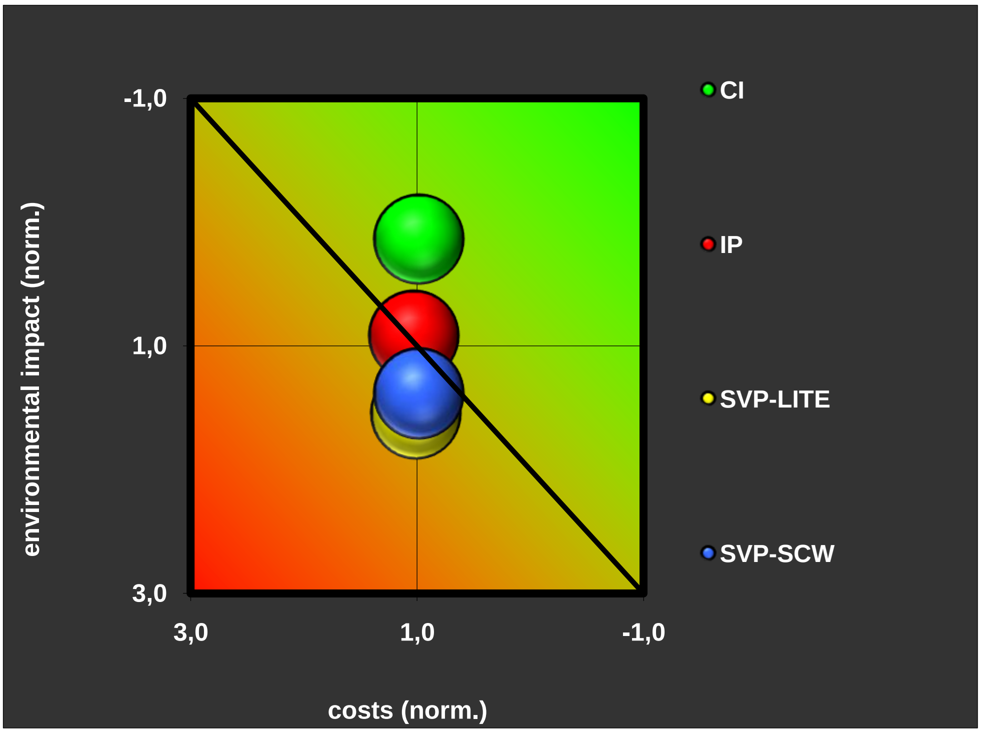

Figure 16. The EEA diagram, Brazilian electricity mix

The weighted and normalized total environmental impact is presented in Figure 17. It shows that the emissions are the most relevant environmental impact category for all four production systems. The resource consumption and the energy use have a similar significance to the total environmental impact. The land use has a small impact on the total environmental impact.

The system with C.I. is the production process which has the smallest total environmental impact of the investigated systems. Its impact is 75 per cent of the impact caused by the system with IP and approximately 60 per cent of the impact caused by the systems with SVP-SCW and SVP-LITE.

The system with SVP-LITE is the production process which has the highest environmental impact disregarding impact category studied. The high impact is due to high resource consumption.

The environmental impact regarding land use is small for the system with C.I. compared to the three other processes.

The weighted resource consumption is lower for all four systems as compared to the base case scenario, especially for the systems with C.I. and IP.

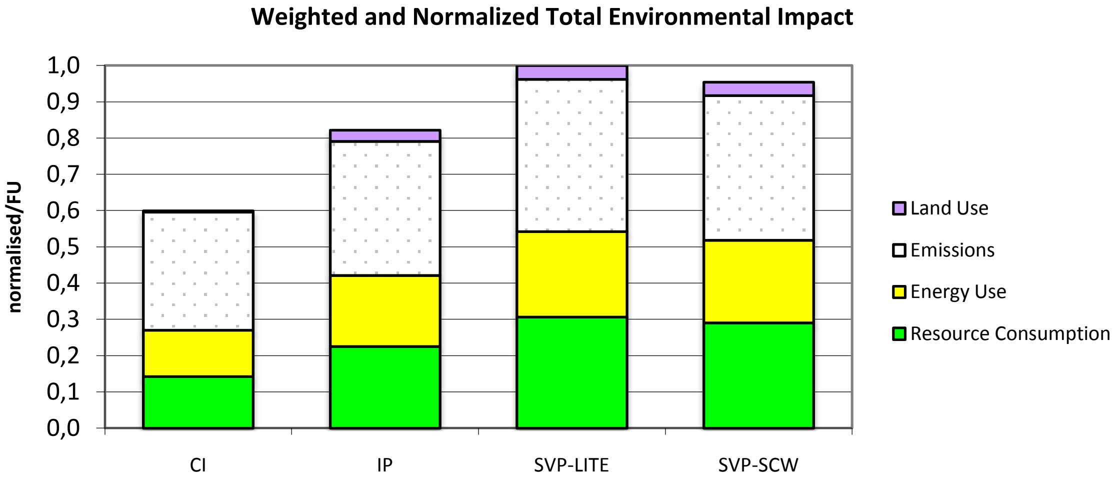

Figure 17. Weighted and normalized total environmental impact, Brazilian electricity scenario.

The weighted results regarding resource consumption are presented in Figure 18. The total weighted resource consumption is in general lower in this scenario than in the base case scenario. The lower resource consumption is especially reflected for the systems with C.I. and IP.

The most significant natural resources in this scenario are, as in the base case scenario, fossil fuels. However, the mix of natural resources differs between this scenario and the base case scenario. For the C.I. system the most significant contribution is made by oil (more than two thirds of the total resources consumed). The IP system also consumes a significant amount of oil. For this system, however, the use of gas, coal and lignite are also significantly contributing to the total resources consumption. This is also the case for the systems with stand-alone chlorine dioxide generators.

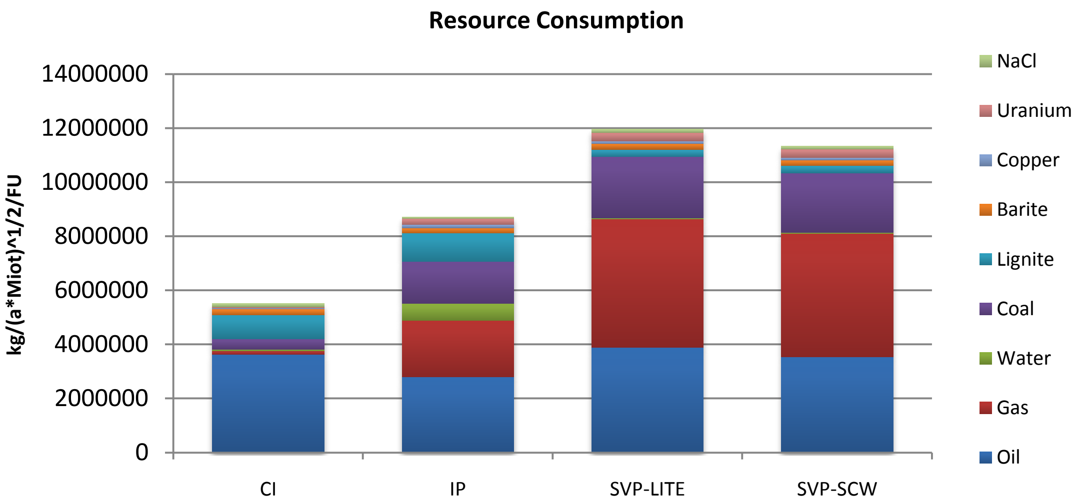

Figure 18. Weighted resource consumption, Brazilian electricity scenario

The results of the total primary energy use are presented in Figure 19. The C.I. system uses the smallest amount of energy (2.3 PJ) followed by the systems with IP, SVP-SCW and SVP-LITE using 3.5 PJ, 4.1 PJ and 4.2 PJ. The share of renewable energy resources is 54 per cent for the C.I. system and 26 per cent for the IP system.

Compared to the base case scenario, the total primary energy consumption is lower when using a Brazilian electricity mix. The difference is largest for the systems with C.I. and IP. The usage of non renewable energy resources for the system with C.I. is almost four times higher in the base case scenario compared to this scenario.

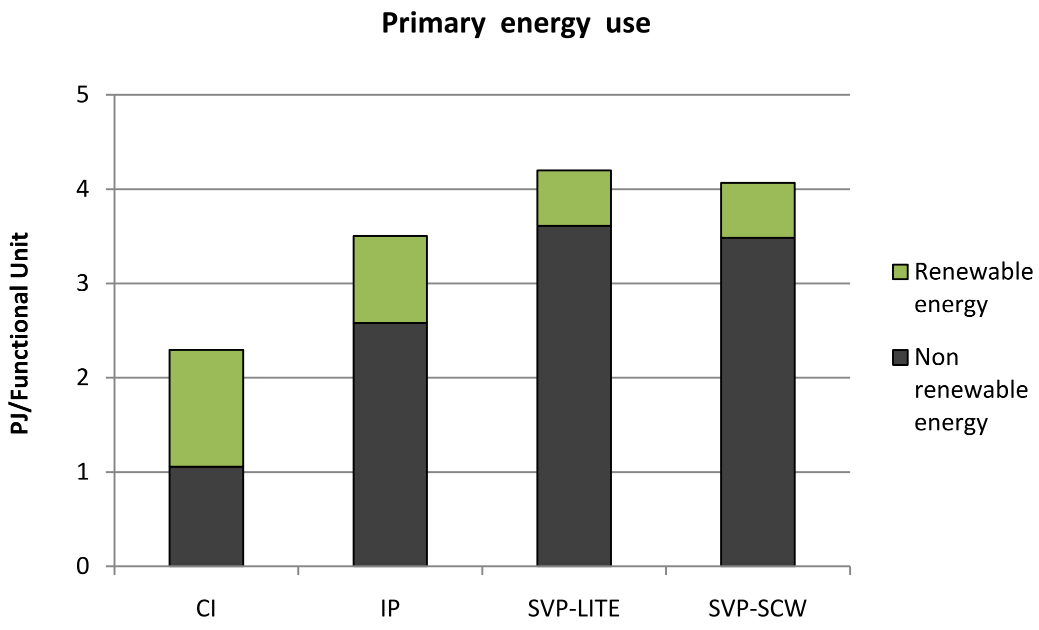

Figure 19 Total primary energy use, Brazilian electricity scenario

The results for the weighted and normalized emissions are presented in Figure 20. Less emissions are generated by the systems with C.I. and IP than by systems with stand-alone chlorine dioxide generators.

The system with C.I. has a low global warming potential, GWP, compared to the other three systems. Its acidification potential, AP, is not considerably lower and the photochemical ozone creation potential, POCP, is actually higher as compared to the system with IP. The systems with stand alone chlorine dioxide generators generate the highest weighted and normalized emissions to air. For those production systems, the global warming potential, GWP, represents the mayor part of the total weighted emissions.

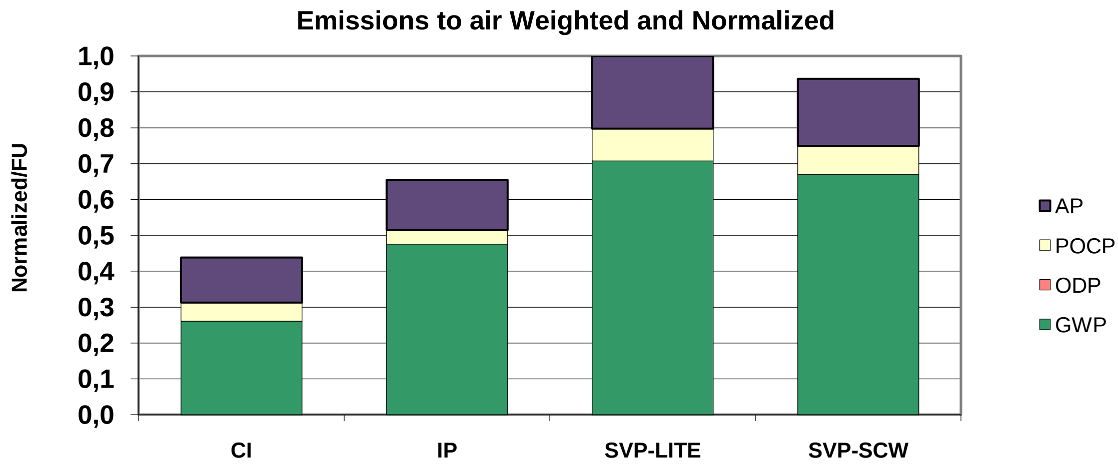

Figure 20. Weighted and normalized emissions to air, Brazilian electricity scenario

3.6.3.3. Indonesia

The result from the Eco-efficiency assessment of the Indonesian electricity scenario is shown in Figure 21. It shows that the two systems with stand-alone chlorine dioxide generators are most eco-efficient, followed by the systems with IP and C.I.. When it comes to environmental impact the differences appear to be quite significant.

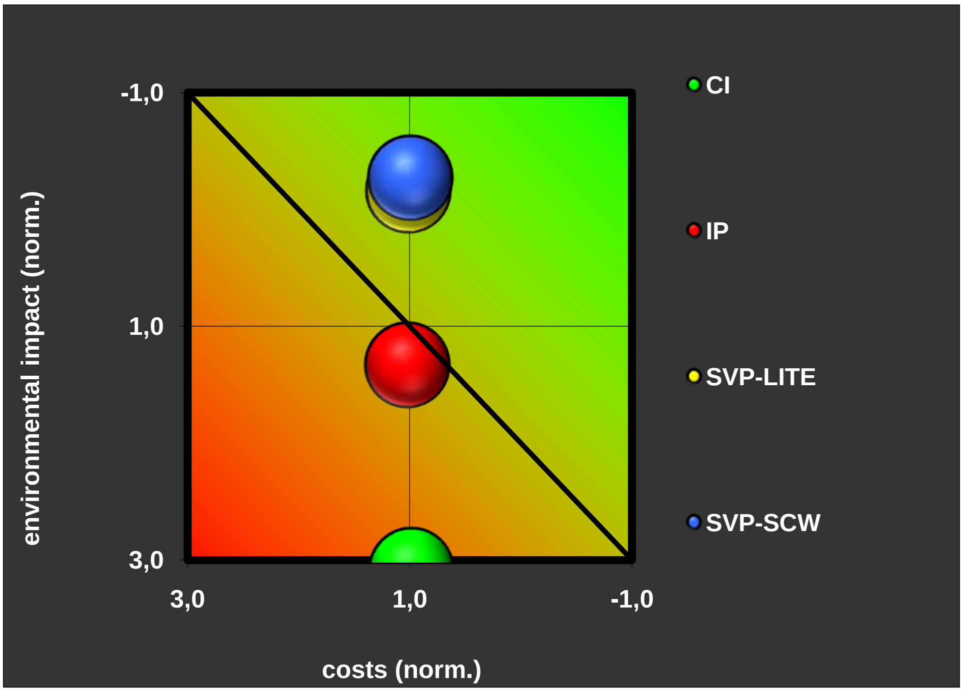

Figure 21. The EEA diagram, Indonesian electricity scenario

The weighted and normalized total environmental impact of the Indonesian electricity scenario is presented in Figure 22. The C.I. system has the highest total environmental impact, more than twice the environmental impact caused by the systems with stand alone chlorine dioxide generators. The emissions contribute significantly to the total environmental impact. The resource consumption for the C.I. system has a higher contribution to the total environmental impact compared to the three other systems. The land use has a relatively small contribution to the total environmental impact for all the alternative production processes.

The system with the SVP-SCW has the lowest total environmental impact of the different production concepts. Its impact is approx 40 per cent compared to the impact of the system with C.I. and approx 60 per cent compared to the system with IP.

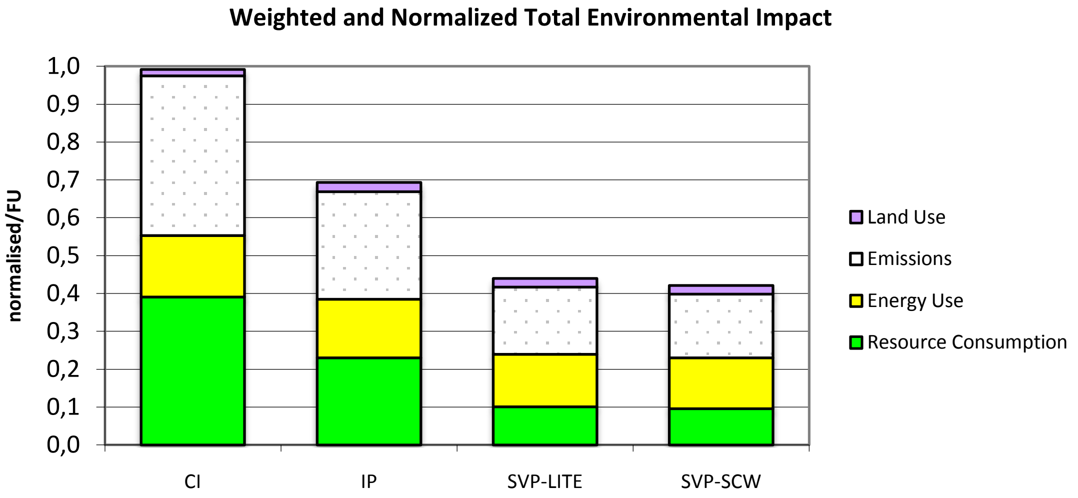

Figure 22. Weighted and normalized total environmental impact, Indonesian electricity scenario

The resource consumption for the Indonesian electricity scenario is presented in Figure 23. The natural resources contributing most are for all four production systems oil, gas, coal, lignite and barite. The lowest resource consumption has the systems with the stand-alone chlorine dioxide generators. These systems consume 25 per cent of the resources compared to the system with C.I. and approx. 40 per cent compared to the one with IP.

For the C.I. and IP systems, the weighted resource consumption is considerably higher for this scenario as compared to the base case scenario. The reason is the use of lignite when producing electricity in Indonesia.

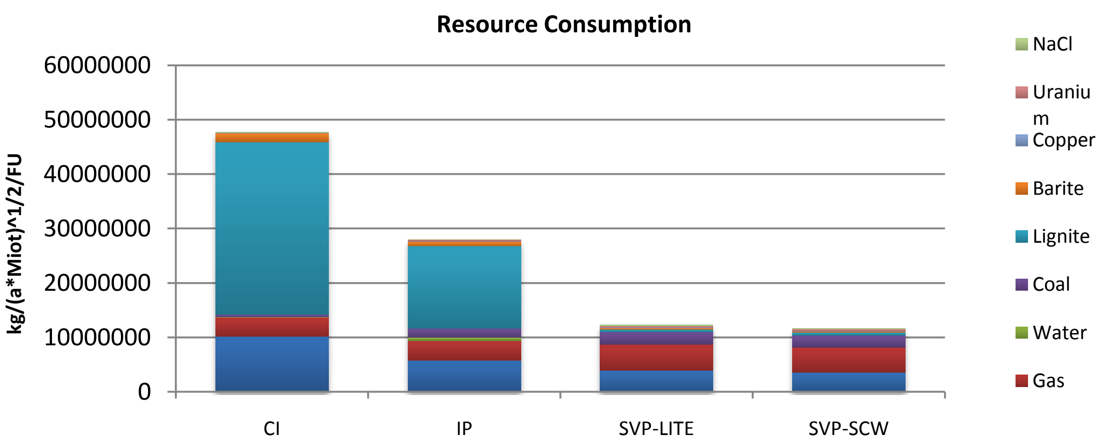

Figure 23 Resource consumption, Indonesian electricity scenario

The total primary energy use in this scenario is presented in Figure 24. It shows that the systems with stand alone chlorine dioxide generators use the smallest amount of primary energy out of the four production concepts. The system with C.I. uses the highest amount (4.9 PJ).

The primary energy use is higher in this scenario as compared to the corresponding primary energy use in the base case scenario. For the systems with C.I. and IP the primary energy use is 13 and 6 per cent higher, respectively. The usage of non renewable energy resources is higher when using an Indonesian electricity mix as compared to the base case scenario.

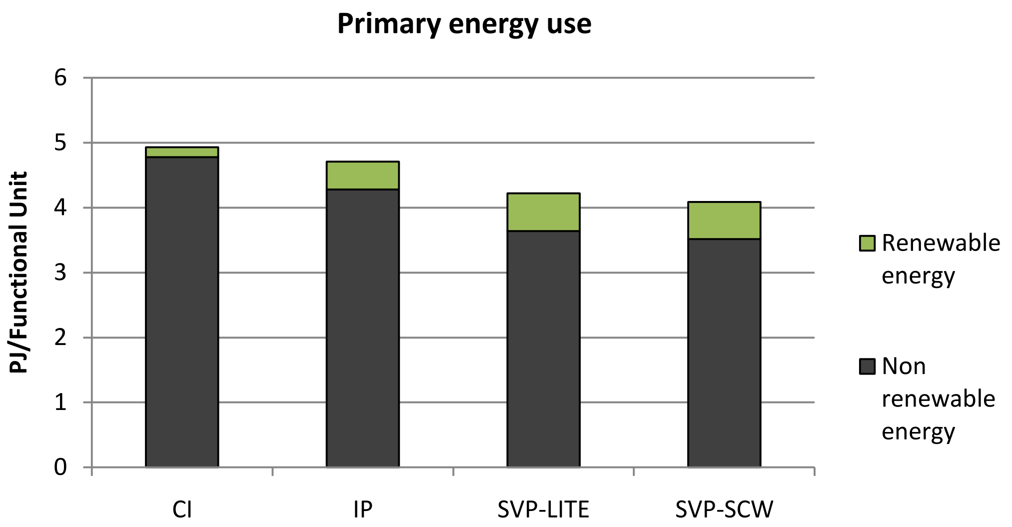

Figure 24 Total primary energy use, Indonesian electricity scenario

The weighted and normalized emissions to air are presented in Figure 25. The global warming potential, GWP is the most relevant air emissions impact category for all four production systems. It is followed by acidification potential, AP and photochemical ozone creation potential, POCP.

The air emissions generated from the system with SVP-SCW has the smallest impact from air emissions of the four production systems compared. Its impact is 43 per cent of the corresponding impact of the C.I. system and 64 per cent of the corresponding impact of the IP system. However, the POCP is highest for the systems with SVP-LITE and SVP-SCW.

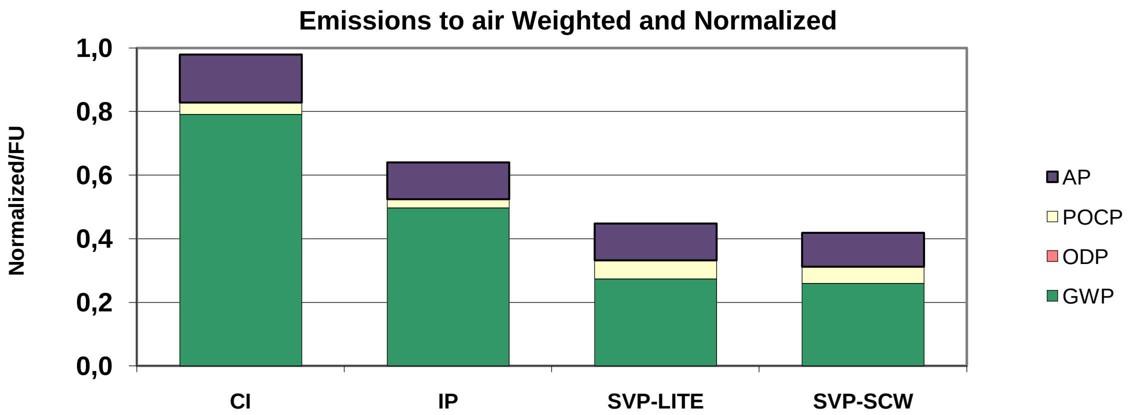

Figure 25 Weighted and normalized emissions to air, Indonesian electricity scenario

3.6.3.4. China

The results from the Eco-efficiency assessment for the scenario using an electricity mix representing China is presented in the EEA diagram (Figure 26). It shows the systems with stand alone chlorine dioxide generators to be most eco-efficient alternatives. The system with C.I. is the least eco-efficient alternative. The difference between the plots in the EEA diagram is bigger for China than the base case scenario. It indicates that the difference in Eco-efficiency between the production systems is bigger in this scenario than in the base case scenario.

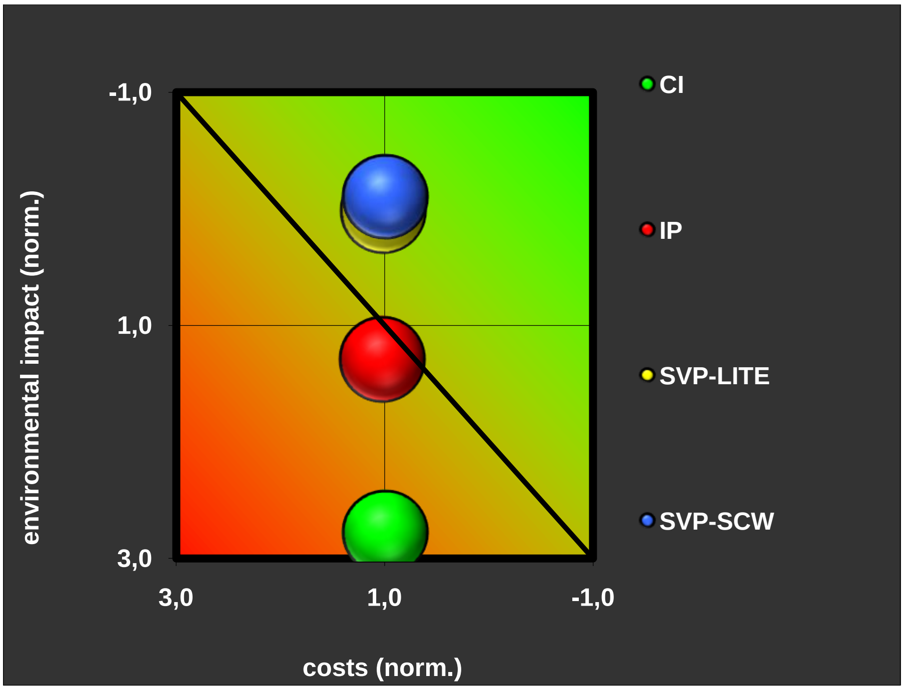

Figure 26 The EEA diagram, Chinese electricity scenario

The weighted and normalized total environmental impact caused by the china scenario is presented in Figure 27. The largest environmental impact is caused by emissions followed by resource consumption, energy use and land use, disregarding production system studied.

The systems with SVP-LITE and SVP-SCW have the lowest total environmental impact of the four production systems. Their impact is 50 per cent of the impact caused by the system with C.I.. The difference in environmental impact between the systems with stand alone chlorine dioxide generators and the systems with C.I. and IP is grander in this scenario than the base case scenario.

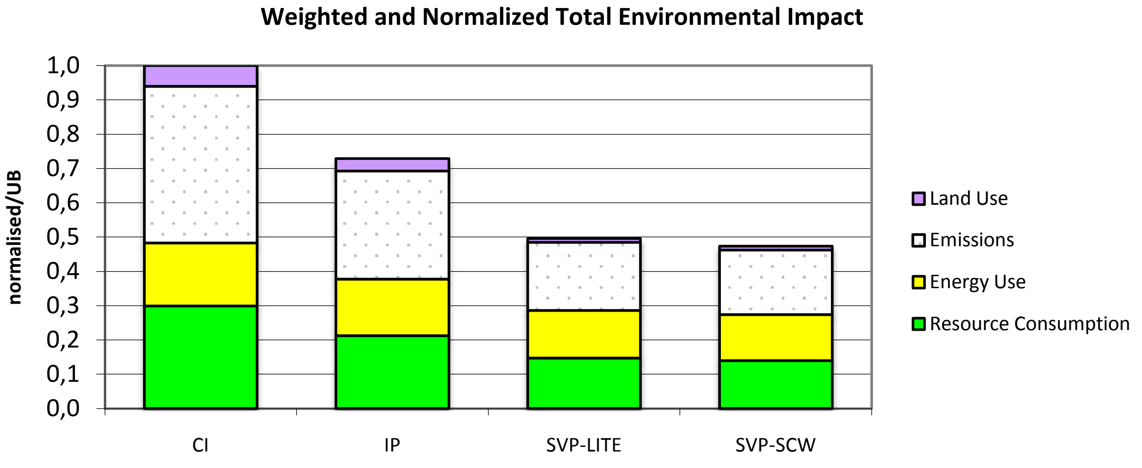

Figure 27 Weighted and normalized total environmental impact, Chinese electricity scenario

The weighted resource consumption is presented in Figure 28. The results show that oil, gas and coal are the natural resources which contribute the most to the total resource consumption. For the systems with SVP-LITE and SVP-SCW, oil, gas and coal are contributing in similar extent to the total consumption. However, in the systems with C.I. and IP oil and lignite are the most dominant resources.

The lowest resource consumption has the system with SVP-SCW, followed by the system with SVP-LITE and IP. The system with C.I. has the highest resource consumption of the four systems. Noticeable is that the resource consumption of coal is higher in this scenario than in the base case scenario for the systems with C.I. and IP.

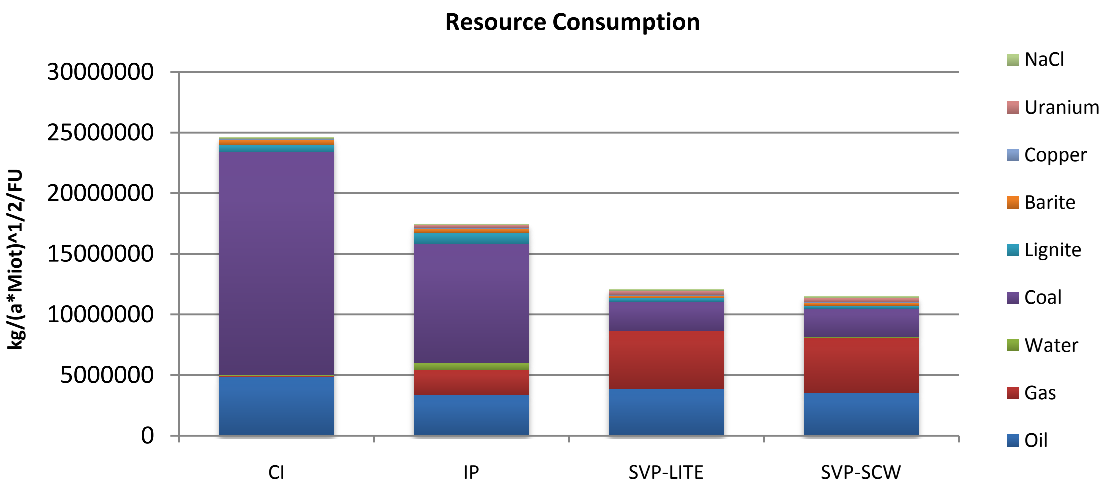

Figure 28 Resource consumption, Chinese electricity scenario

The total primary energy use in this scenario is presented in Figure 29. The systems with stand-alone chlorine dioxide generators have the lowest use of primary energy. The systems with C.I. and IP use 5.6 PJ and 5.0 PJ, respectively. The share of renewable energy resources is 5 and 9 per cent for the systems with C.I. and IP, respectively.

The primary energy use is higher in this scenario compared to the base case scenario, disregarding production concept studied. However, the largest increase in primary energy use is found the systems with C.I. and IP. Further on, the share of renewable energy resources is lower in this scenario as compared to the base case scenario.

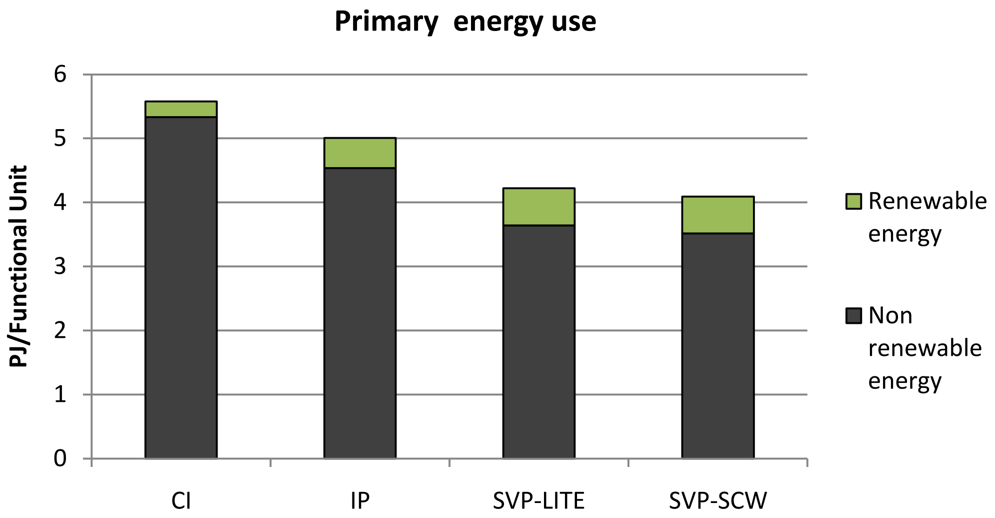

Figure 29 Total primary energy use, Chinese electricity scenario.

The weighted and normalized emissions to air are presented in Figure 30. The result shows that the dominant impact category is global warming potential, GWP, especially for the systems with C.I. and IP. The system with C.I. also has the highest acidification potential, AP, of the four production concepts compared.

The systems with stand alone chlorine dioxide generators have the lowest total weighted and normalized emissions to air. Nevertheless, the photochemical ozone creation potential, POCP, is higher for those systems than for the systems with C.I. and IP.

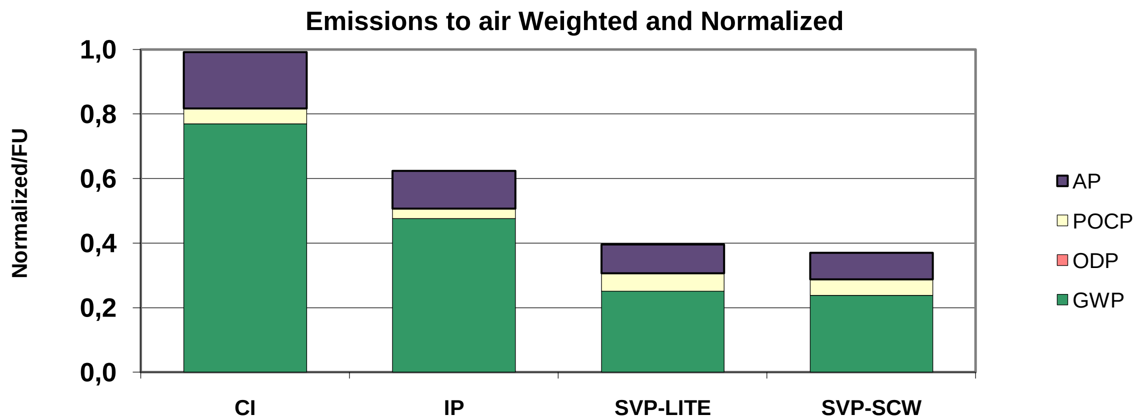

Figure 30 Weighted and normalized emissions to air, Chinese electricity scenario

3.6.3.5. Transportation Scenario

This scenario represents a background system where the properties of the transportations are changed as compared to the base case scenario. The transportation distance is 300 km which is performed by truck, instead of train. A detailed description of this scenario can be found in the chapter transportation scenario.

The eco-efficiency assessment result from the transportation scenario is presented in the EEA diagram, Figure 31. The system with SVP-SCW is the most eco-efficient option. It is closely followed by the system with SVP-LITE. The systems with IP and C.I. are less eco-efficient. The ranking is not changed as compared to the base case scenario.

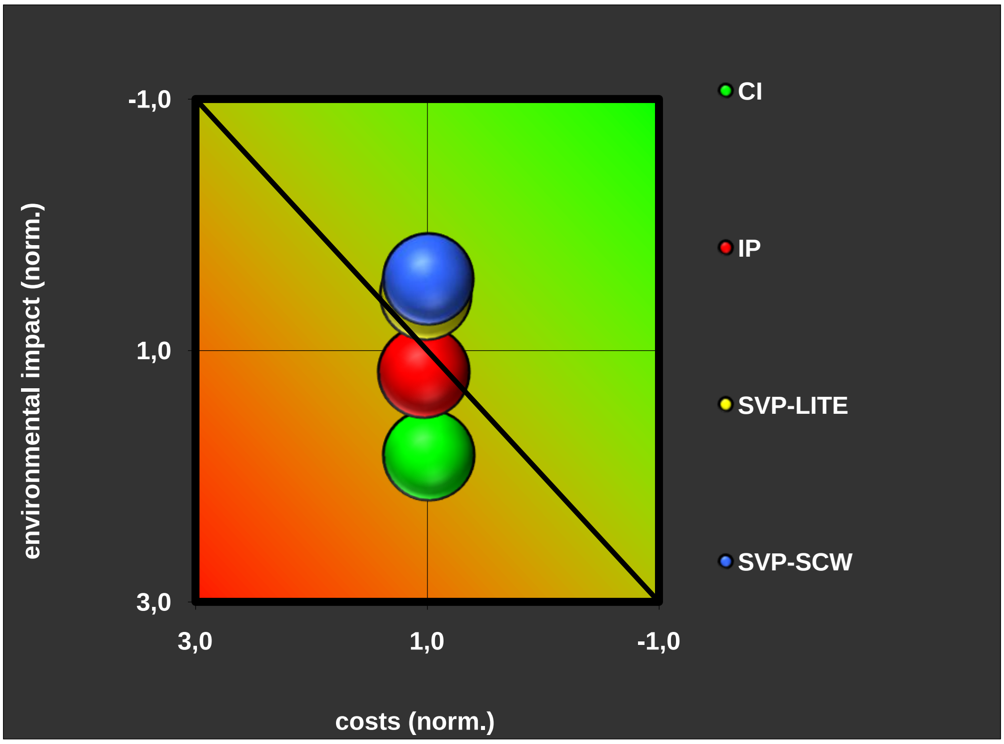

Figure 31 The EEA diagram for the transportation scenario

The weighted and normalized total environmental impact for the transportation scenario is presented in Figure 32. For all four production systems, the emissions generated contribute most to the total weighted environmental impact. It isfollowed by the resource consumption, the energy use and the land use. The impact of the land use is small compared to the others.

The systems with SVP-LITE and SVP-SCW have the lowest environmental impact of the four production systems. The C.I. system has the highest impact for all four impact categories investigated. The total environmnetal impact is not noticably changed in this scenario as compared to the base case scenario.

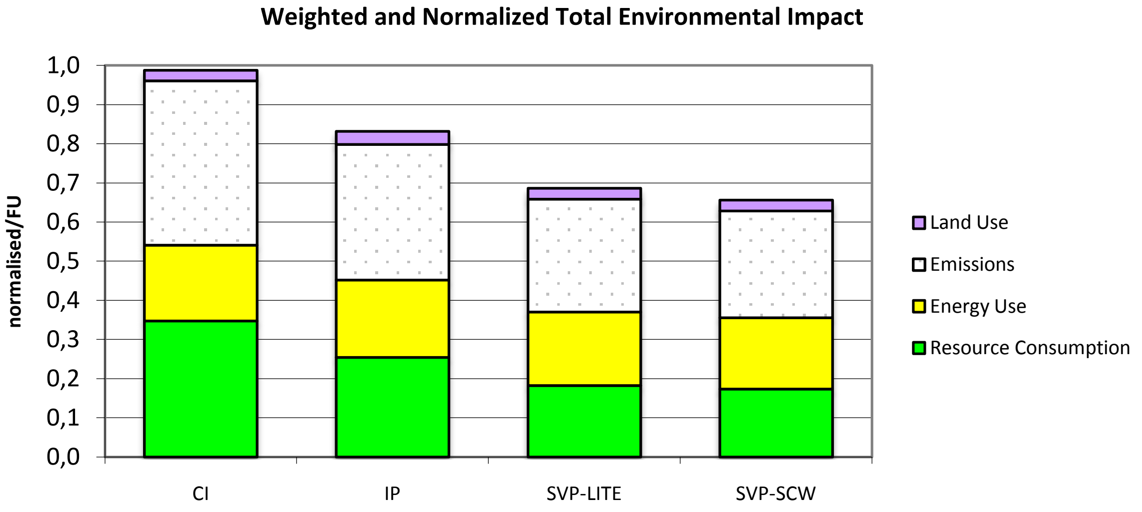

Figure 32 Weighted and normalized total environmental impact, transportation scenario

The weighted resource consumption is presented in Figure 33. It shows that the most relevant resources consumed by the four production processes are oil, gas, coal, lignite and barite. The most dominant resource is gas.

The systems with SVP-LITE and SVP-SCW have the lowest consumption of natural resources. The consumption of resources is twice as high for the C.I. system as compared to the SVP-SCW system.

The total weighted resource consumption is marginally lower in this scenario as compared to the base case scenario.

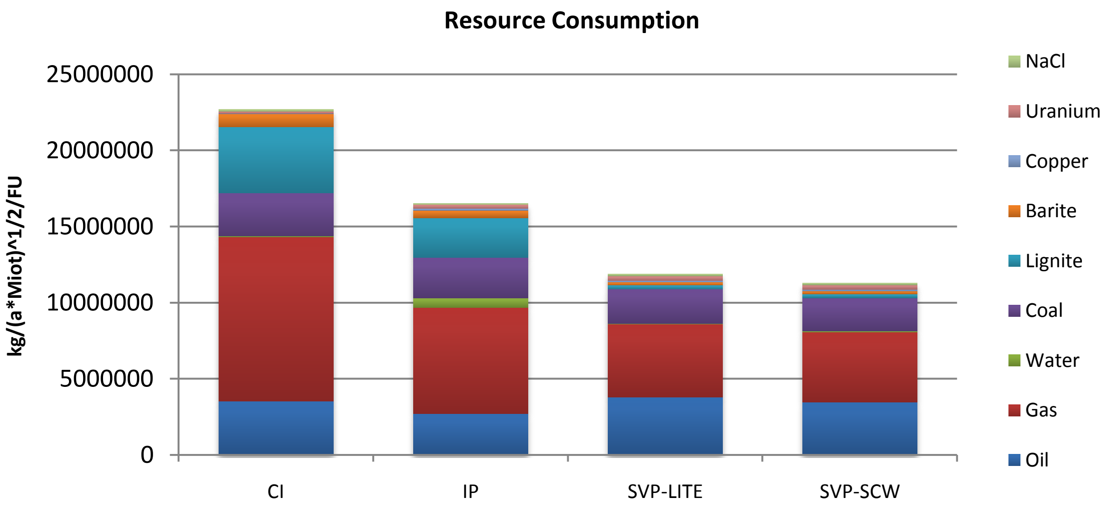

Figure 33 Weighted resource consumption, transportation scenario.

The total primary energy use in the transportation scenario is presented in Figure 34. The system with IP is using the largest amount of primary energy (4.4 PJ), followed by the systems with C.I. (4.3 PJ), SVP-LITE (4.2 PJ) and SVP-SCW (4.1 PJ). The share of renewable energy use is highest for the systems with the stand-alone chlorine dioxide generators.

The total primary energy use is lower for all four production systems in the transportation scenario as compared to the base case scenario. The difference is, however, less than one per cent.

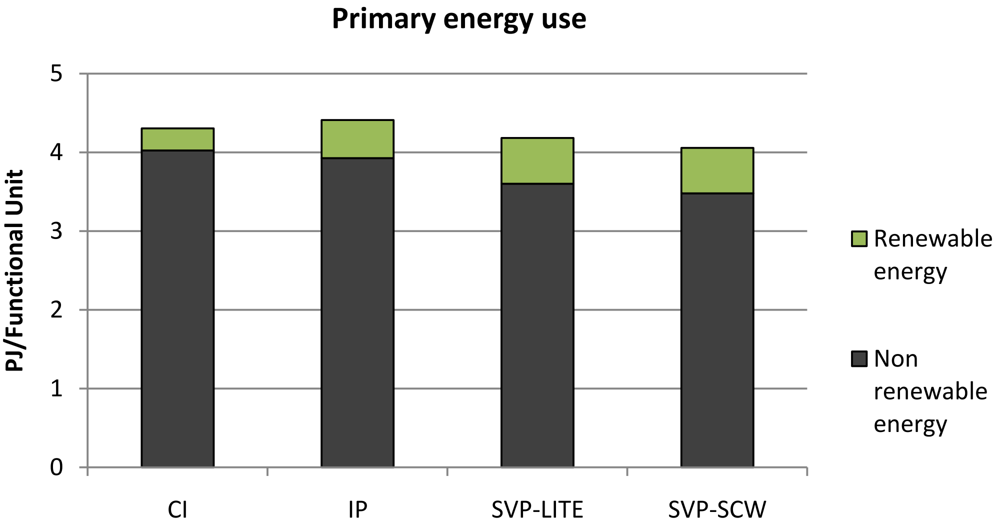

Figure 34 Total primary energy use, transportation scenario.

Finally, the emissions generated by the transportation scenario is weighted and normalized according to Figure 35. The global warming potential, GWP, is the most relevant impact category regarding emissions to air for all four production systems. It is followed by the acidification potential, AP, and the photochemical ozone creation potential, POCP.

The C.I. system has the highest contribution to the impact category air emissions. The systems with stand alone chlorine dioxide generators have the lowest contribution in total and to the categories global warming potential, GWP, and acidification potential, AP. These two systems, however, have the highest photochemical ozone creation potential, POCP. The results of the weighted and normalized emissions to air are not differentiated to the results in the base case scenario.

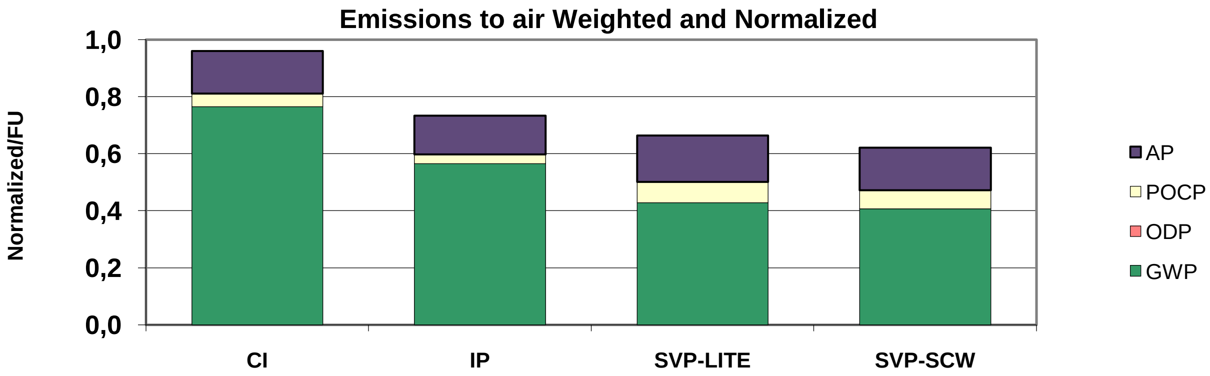

Figure 35 The emissions to air weighted and normalized for the four production systems, divided into the environmental impact categories AP, POCP, ODP and GWP.

3.6.4. Foreground system

The results obtained when making the same comparison as in the base case but for scenarios with varying assumptions related to characteristics of the foreground system are presented in this chapter. The scenarios are:

- the sodium hydroxide scenario
- the no sodium chlorate scenario; and
- the no sodium sulfate scenario.

The scenarios are defined in the chapter Scenarios and their properties are compiled in table 1.

3.6.4.1. Sodium Hydroxide Scenario

In the sodium hydroxide scenario, the system with IP, has an on-site chlorine alkali process, dimensioned to produce and supply the entire pulp mill demand for sodium hydroxide. Thus, no sodium hydroxide needs to be delivered from the open market. However, a surplus of chlorine is generated in the chlorine alkali process which not is utilized by the system. This surplus of chlorine is assumed to be sold to the open market in the region. The systems with SVP-LITE, SVP-SCW and C.I. are not affected by the assumptions in this scenario.

The result from the eco efficiency assessment is presented in the EEA diagram, Figure 36. The system with SVP-SCW is the most eco-efficient alternative, closely followed by the SVP-LITE system. The system with IP comes more close to the systems with chlorine dioxide generators. The system with C.I. has the highest environmental impact. The ranking in terms of eco-efficiency is the same as in the base case scenario.

For costs, the alternative production concepts are not easily differentiated. Thus, it is not possible to rank the production concepts in terms of cost performance, using the EEA diagram.

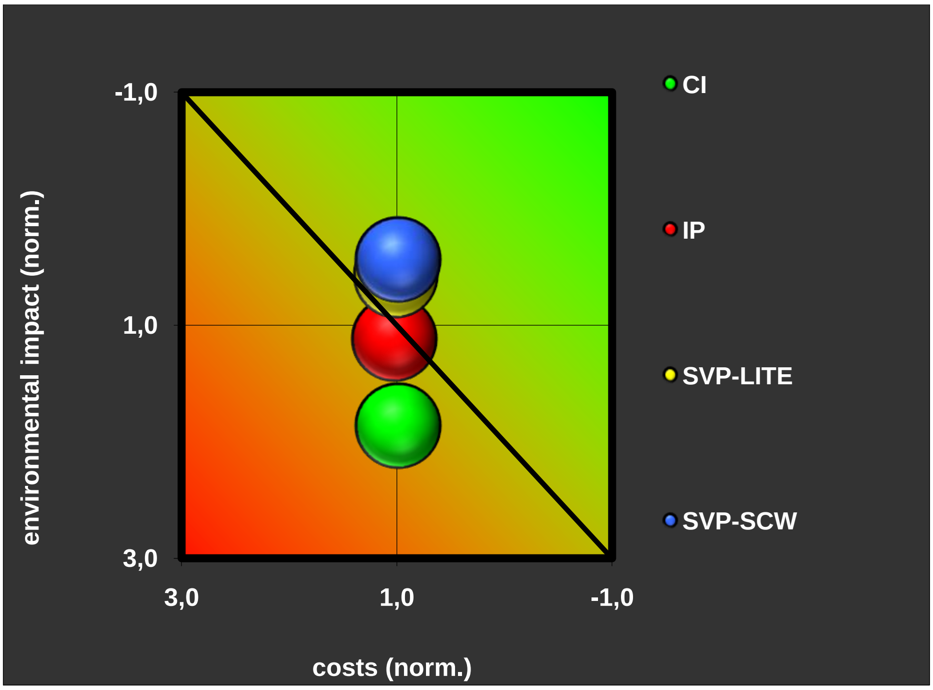

Figure 36 The EEA diagram, sodium hydroxide scenario.

The weighted and normalized total environmental impact is presented in Figure 37. The emissions generated by the four production concepts have the highest environmental impact followed by the resource consumption, energy use and land use. Land use contributes little to the total weighted environmental impact.

The results further show that the SVP-SCW system is the alternative with the smallest total environmental impact, followed by SVP-LITE, IP and C.I.. The system with C.I. has the largest environmental impact regardless impact category studied.

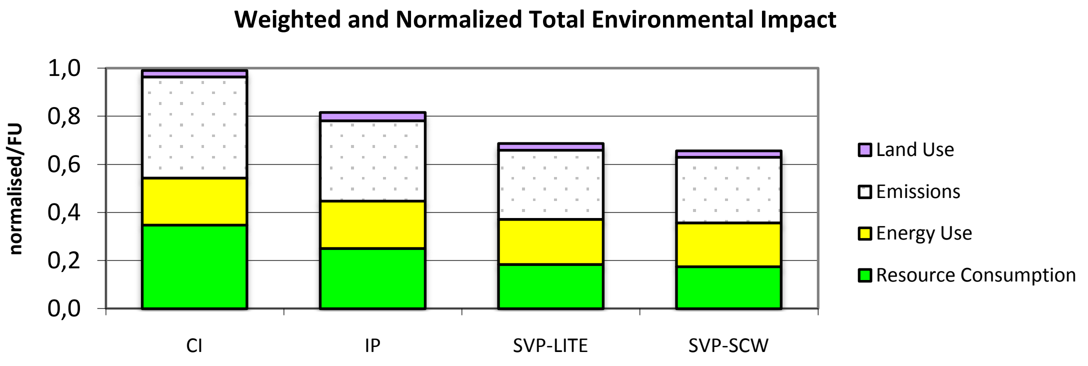

Figure 37 Weighted and normalized total environmental impact, sodium hydroxide scenario

The weighted resource consumption is presented in Figure 38. Oil, gas, coal, lignite and barite are the most important of the natural resources consumed. For the systems with SVP-SCW and SVP-LITE uranium and sodium chloride are also important natural resources consumed.

The systems with stand alone chlorine dioxide generators are the best ones with respect to consumption of natural resources. Their weighted resource consumption is half of the corresponding C.I. system consumption and two thirds of the corresponding IP system consumption.

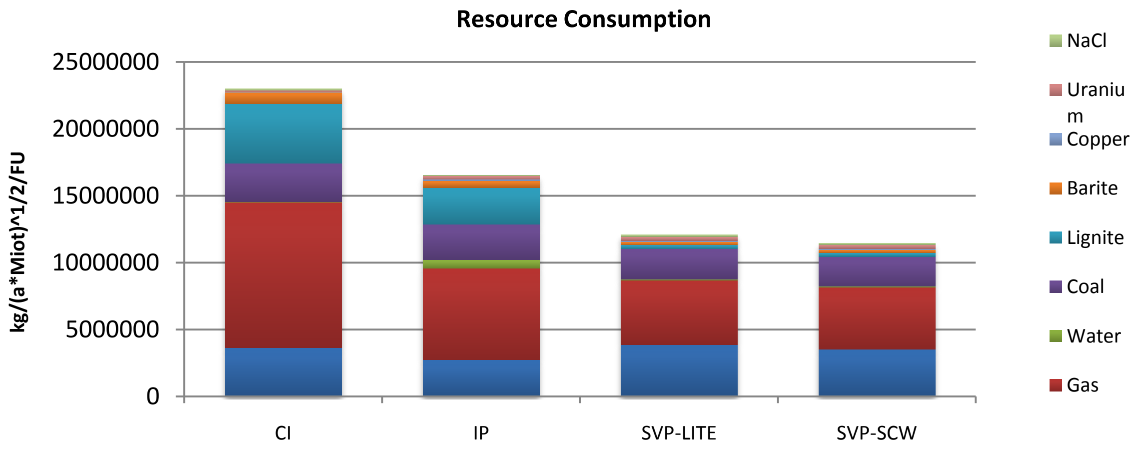

Figure 38. Weighted resource consumption, sodium hydroxide scenario

The total use of primary energy is presented in Figure 39. The system with IP requires the largest amount of primary energy (4.4 PJ). It is followed by the systems with C.I. (4.4 PJ), SVP-LITE (4.2 PJ) and SVP-SCW (4.1 PJ). The quote between renewable energy use and non renewable energy use is equal for the systems with SVP-LITE and SVP-SCW. However, this quote is smaller for the systems with IP and C.I..

The consumption of primary energy is not changed in this scenario compared to the base case for the systems with C.I., SVP-LITE and SVP-SCW. However, the primary energy use for the system with IP is somewhat less in this scenario compared to the base case.

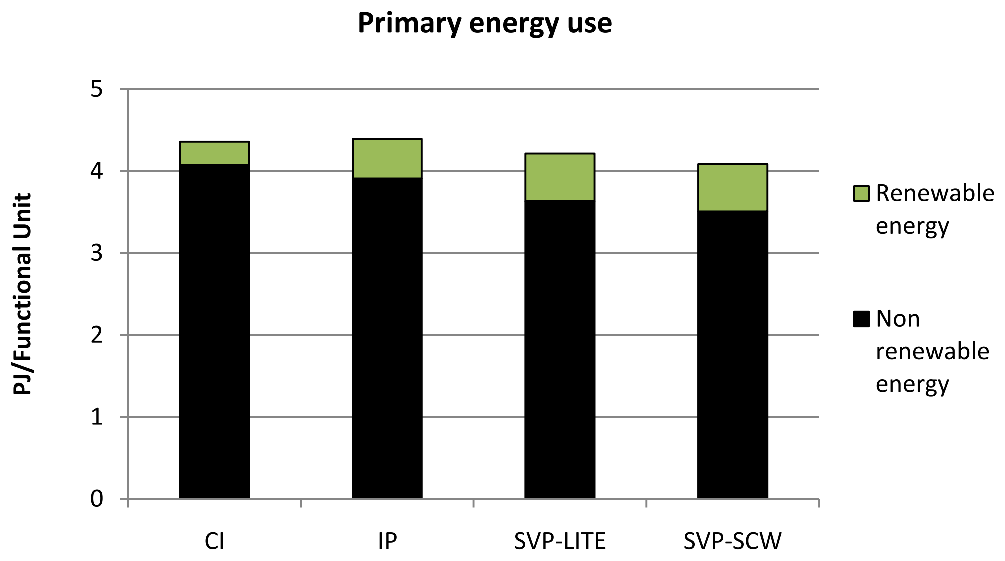

Figure 39 Total primary energy use, sodium hydroxide scenario

The weighted and normalized emission to air result is presented in Figure 40. It shows that the systems with stand alone chlorine dioxide generators contribute the least to this impact category, closely followed by the IP system. The global warming potential (GWP) is the impact category with the highest relevance for emissions to air. The SVP-SCW system GWP is half the GWP of the C.I. system C.I. and 75 per cent of the IP system GWP. With respect to acidification (AP) and photo chemical ozone creation(POCP), the systems with chlorine dioxide generators contribute more than the systems with IP and C.I..

Further on, the IP system contributes the least to both acidification and photochemical ozone formation.

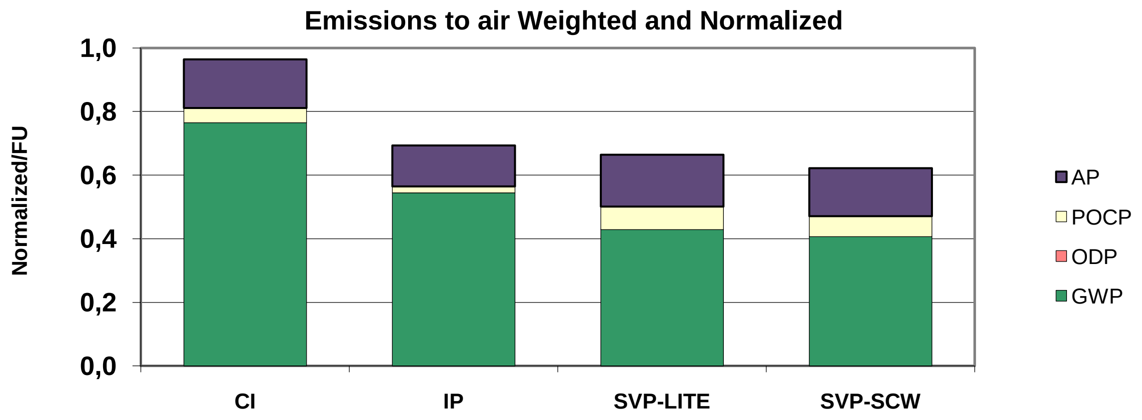

Figure 40 Weighted and normalized emissions to air, sodium hydroxide scenario

3.6.4.2. No Sodium Chlorate Scenario

In this scenario it is assumed that there is no market demand for sodium chlorate. Thus, the sodium chlorate is excluded from the functional unit. This means that the systems with chlorine dioxide generators and IP do not have to deliver sodium chlorate from Alby and Oulu as in the base case scenario. Likewise, the sodium chlorate plant in the C.I. system does not need to be dimensioned to produce and supply extra sodium chlorate.

The EEA diagram for the no sodium chlorate scenario is presented in Figure 41. It shows that the systems with SVP-SCW and SVP-LITE are the most eco-efficient alternatives. The EEA diagram further shows that the system with C.I. is somewhat more eco-efficient than the IP system. Compared to the base case scenario, the ranking of the C.I. and IP systems is reversed.

As for the base case and the sodium hydroxide scenarios, it is not possible to rank the production concepts in terms of cost performance by use of the EEA diagram.

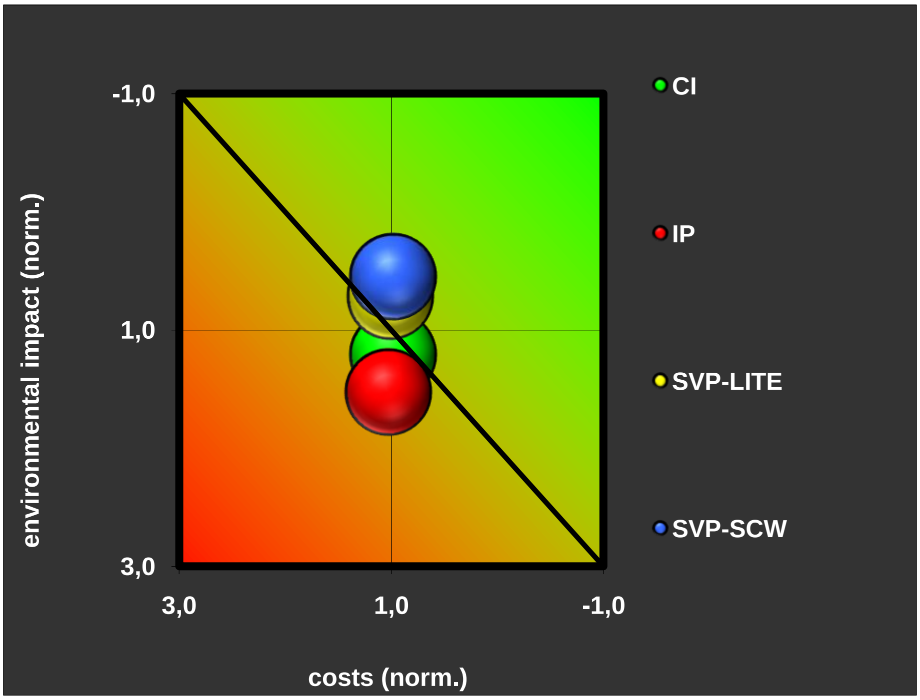

Figure 41 The EEA diagram, no sodium chlorate scenario

The results of the weighted and normalized total environmental impact caused by the four alternative production systems are presented in Figure 42. The system utilizing SVP-SCW is the production system which has the lowest environmental impact, regardless of environmental impact category studied. The largest environmental impact is caused by IP system.

The results show that the differences in total environmental impact between the alternative systems are smaller in this scenario compared to the base case scenario.

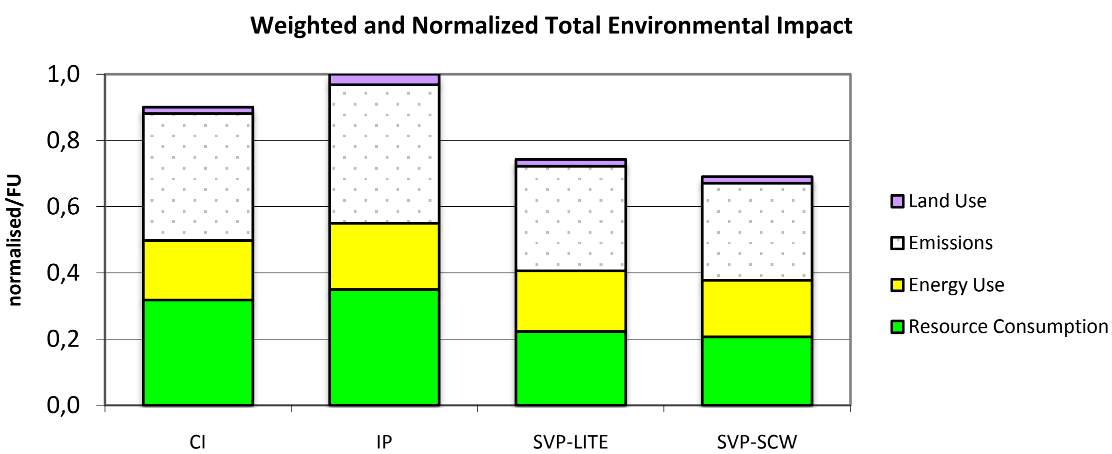

Figure 42 Weighted and normalized total environmental impact, no sodium chlorate scenario

The resource consumption for the four systems studied are presented in Figure 43. The resources contributing the most are for all four production systems oil, gas, coal, lignite and barite. Water is consumed on a larger scale for the system with IP than for the others. The systems with stand alone chlorine dioxide generators have the lowest consumption of natural resources. However, the difference in consumption between those two systems and the systems with IP and C.I. is smaller compared to the base case.

Compared to the base case scenario, the consumption of natural resources is lower for all four production systems in this scenario. For the C.I. and IP systems the differences in resource consumption between this scenario and the base case scenario are significant. In this scenario, the resource consumption of the C.I. system is half as compared to the base case scenario. The corresponding figure for the IP system is approximately 80 per cent.

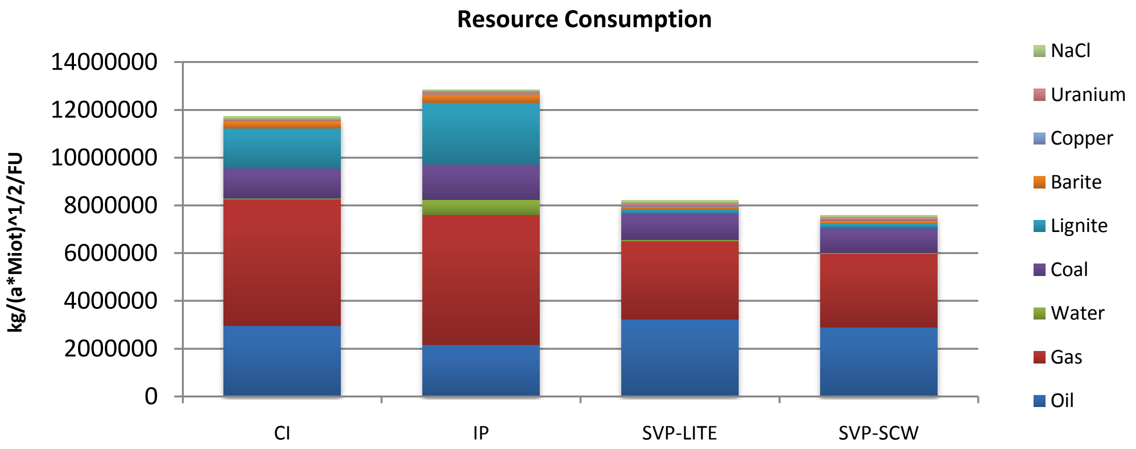

Figure 43 Weighted resource consumption, no sodium chlorate scenario

The total primary energy use is presented in Figure 44. It shows that the system with IP utilizes the largest amount of energy (2.5 PJ). It is followed by the systems with SVP-LITE and C.I. (2.3 PJ) and SVP-SCW (2.2 PJ). The share of renewable energy use is 5 per cent for the systems with C.I. and IP. For the systems with SVP-LITE and SVP-SCW, the corresponding share is 10 per cent.

Just as the consumption of natural resources, the total primary energy use is considerably lower in this scenario compared to the base case scenario. The ranking of the alternatives compared with respect to primary energy use is shifted in this scenario compared to the base case; In this scenario, the SVP-LITE system has a somewhat higher primary energy use than the C.I. system. Further on, the share of renewable energy use is lower for the IP system in this scenario as compared to the base case.

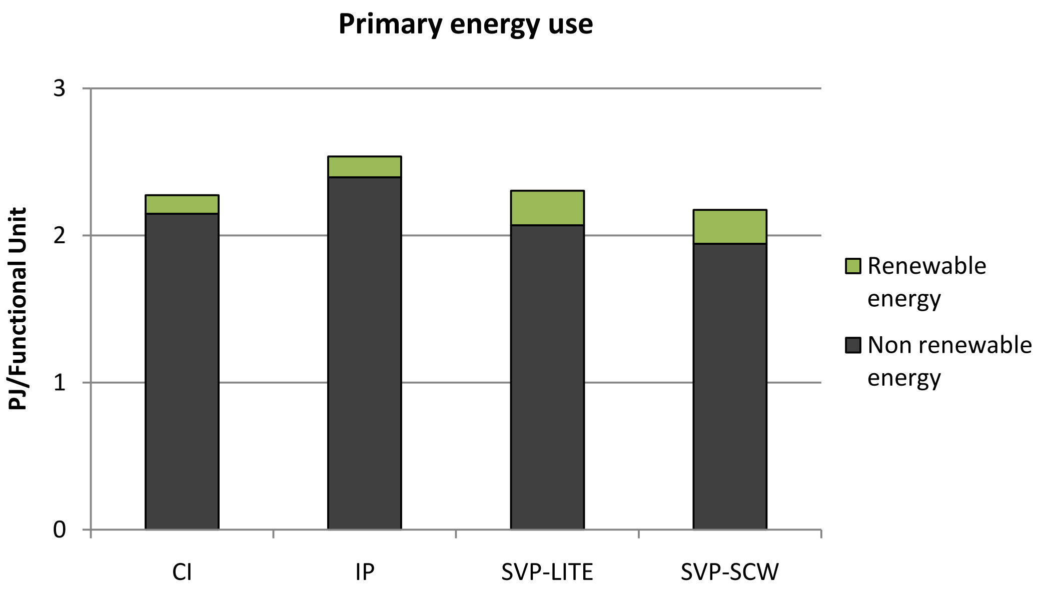

Figure 44 Total primary energy use, no sodium chlorate scenario

The weighted and normalized emissions to air for the four production systems are presented in Figure 45. For all four production systems the global warming potential, GWP, is the largest contributor to the total environmental impact caused by emissions to air. However, the acidification potential, AP, and the photochemical ozone creation potential, POCP, are also contributing.

The systems with stand alone chlorine dioxide generators show the smallest impact in the category emissions to air. The GWP of these systems is 62 per cent as compared to the GWP of the IP system. However, both the AP and the POCP are higher for the systems with stand alone chlorine dioxide generators than for the IP and C.I. systems.

Noticeable is that the total impact due to air emissions are very close for the C.I. and IP systems. The C.I. system has the highest AP and POCP, whilst the IP system has the highest GWP.

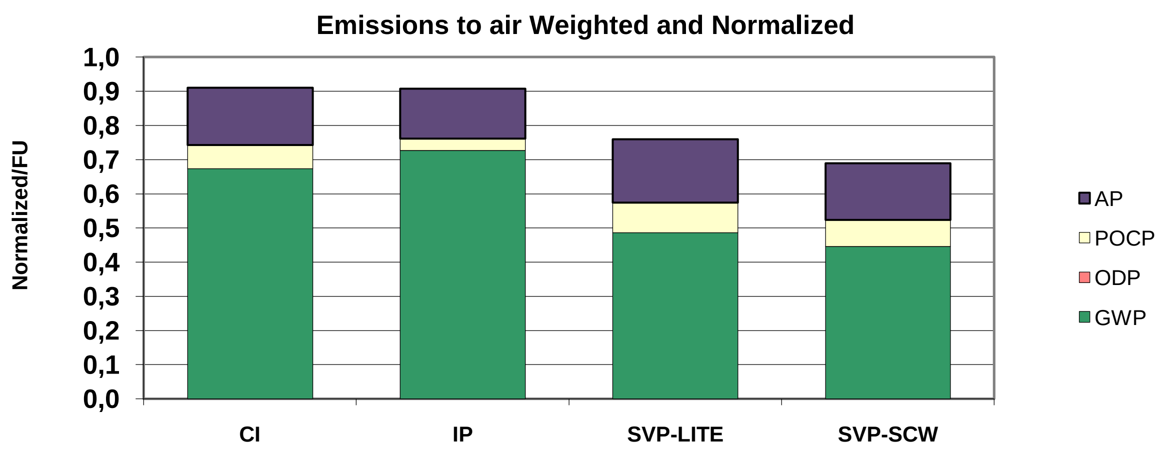

Figure 45 Weighted and normalized emissions to air, no sodium chlorate scenario

3.6.4.3. *No sodium sulfate scenario*

This scenario is based on the assumption that sodium sulfate is not demanded by the pulp mill. Thus, in this scenario, the functional unit is changed as compared to the base case. 14 850 tonnes of sodium sulfate is not included in the functional unit. The sodium sulfate generated in the systems with C.I., SVP-LITE and SVP-SCW is instead regarded as waste and sent to landfill. Further on, for the IP system, there is no need to deliver sodium sulfate from external sources.

The result from the eco-efficiency assessment for this scenario is presented in the EEA diagram in Figure 46. The results show that the system with SVP-SCW is the most eco efficient alternative closely followed by the systems with SVP-LITE and IP. In this scenario, the C.I. system is the least eco-efficient alternative. The ranking is not changed compared to the base case scenario. However, the SVP-SCW, SVP-LITE and IP alternatives are closer.

As for the other scenarios, it is not possible to rank the production concepts in terms of cost performance by use of the EEA diagram.

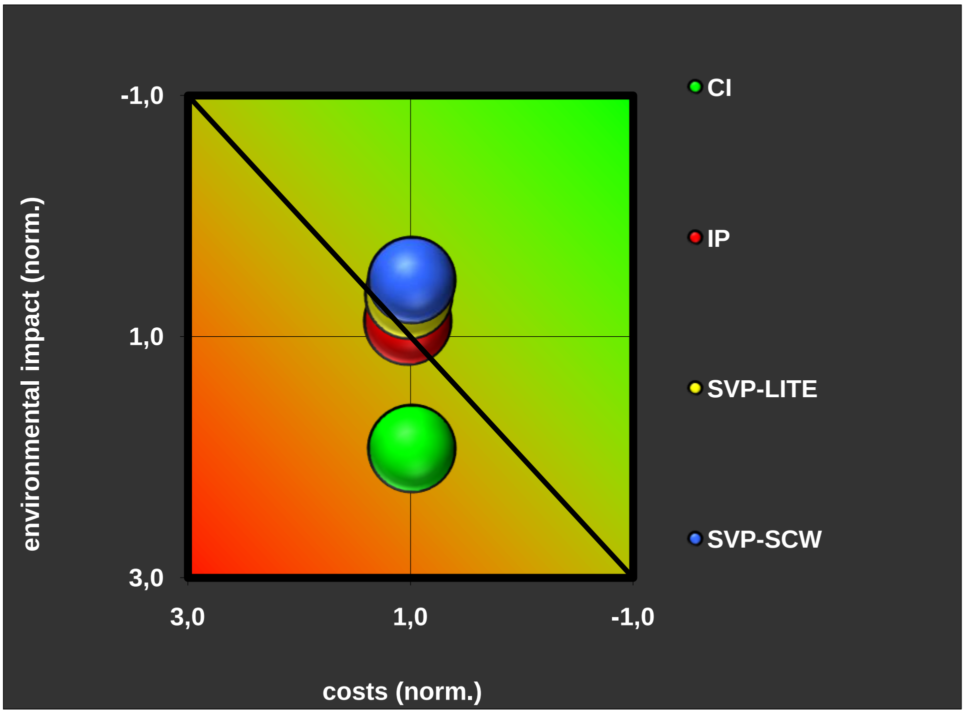

Figure 46 The EEA diagram, no sodium sulfate scenario.

The weighted and normalized total environmental impact is presented in Figure 47. It shows that the emissions contribute most for all four production systems, followed by resource consumption, energy use and land use. The impact of land use is small compared to the other impact categories.

Further on, the two systems with stand alone chlorine dioxide generators are the ones causing the smallest total environmental impact. The difference in environmental impact between these two systems and the IP system is smaller in this scenario than in the base case scenario. The highest environmental impact is caused by the system with C.I..

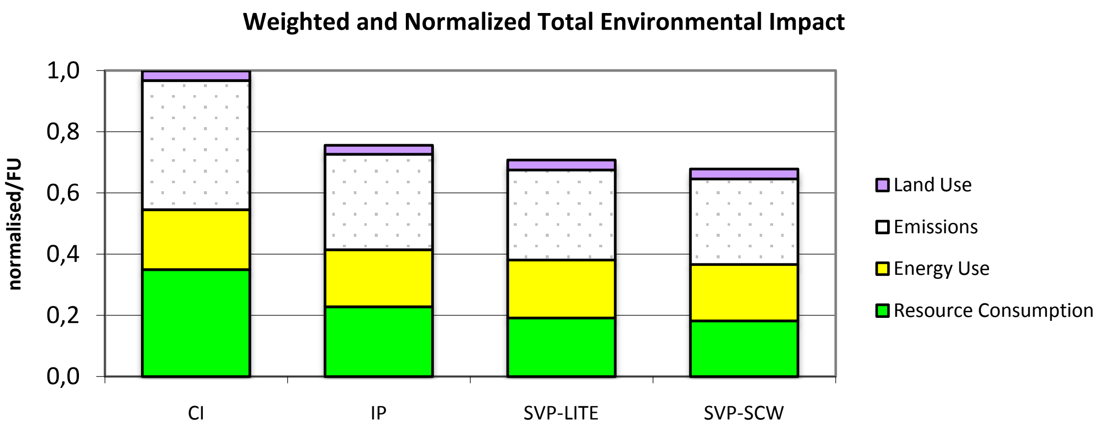

Figure 47 Weighted and normalized total environmental impact, no sodium sulfate scenario

The resource consumption in the sodium sulphate scenario is presnted in Figure 48. For all four production systems, the natural resources contributing the most are oil, gas, coal, lignite and barrite. The system with IP consumes a larger amount of water than the other three systems.

The natural resources consumption of the SVP-SCW and the SVP-LITE systems is half the consumption of the C.I. system and 75 per cent the consumption of the IP system.

The ranking of the four production systems is not changed compared to the base case scenario. However, the resource consumption is higher in this scenario than the the base case scenario for the systems with C.I., SVP-LITE and SVP-SCW. The system with IP consumes a smaller amount of weighted resources than in the base case scenario.

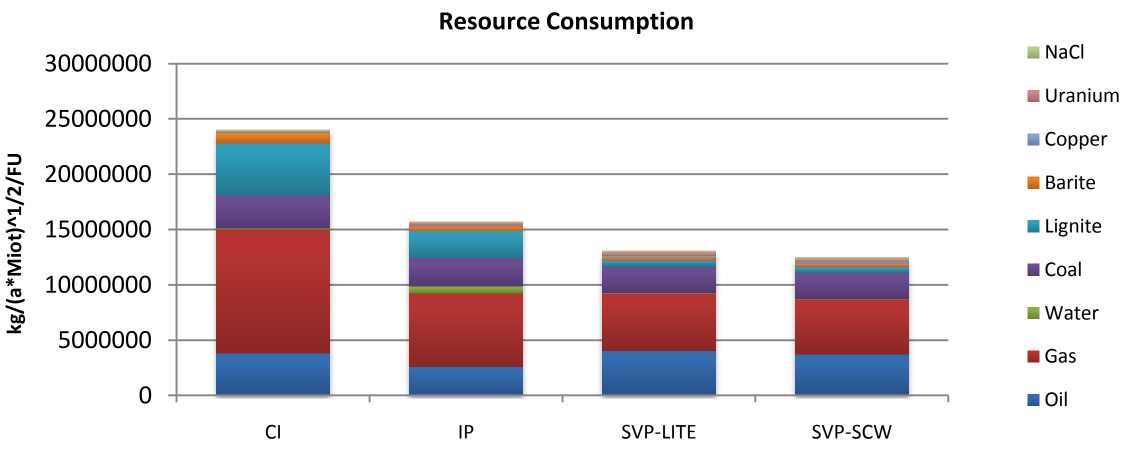

Figure 48 Weighted resource consumption, sodium sulfate scenario.

The total primary energy use for this scenario is presented in Figure 49. It shows that the C.I. system utilizes the largest amount of primary energy (4.5 PJ). It is followed by the systems with SVP-LITE (4.4 PJ), IP (4.3 PJ) and SVP-SCW (4.248 PJ). The share of renewable energy is larger than one tenth for the systems with IP and stand alone chlorine dioxide generators and six per cent for the system with IP.

The primary energy use is four per cent lower for the IP system in this scenario as compared to the base case. For the systems with C.I., SVP-LITE and SVP-SCW it is four per cent higher.

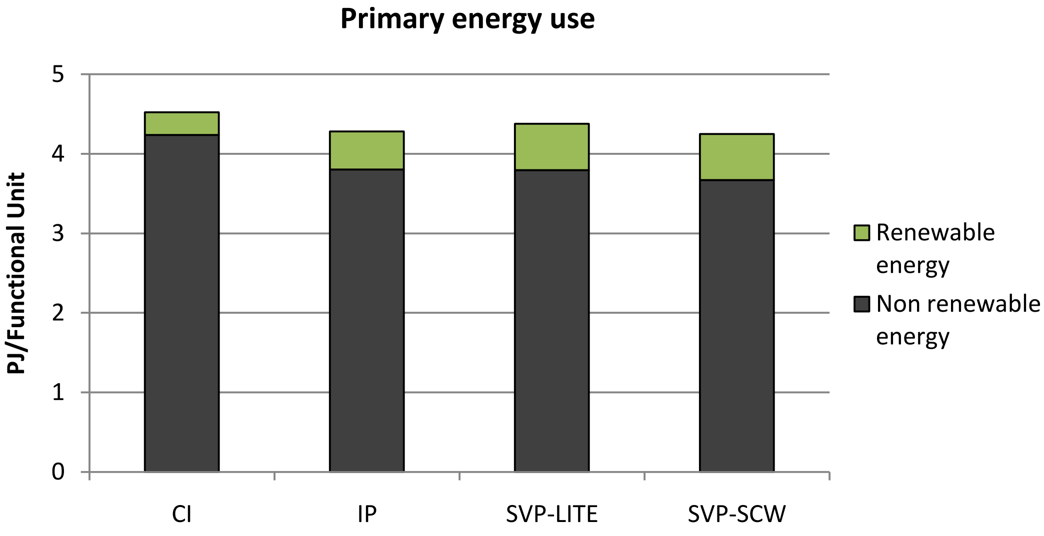

Figure 49 Total primary energy use, no sodium sulfate scenario

The weighted and normalized emission to air for the no sodium sulfate scenario is presented in Figure 50. For all four production concepts compared, the global warming potential, GWP, is the impact category contributing most. It is followed by the acidification potential, AP, and the photo chemical ozone creation potential, POCP.

The ranking between the four production systems is changed as compared to the base case scenario. The environmental impact of emissions to air generated by the IP system is lower in this scenario compared to the base case scenario. When it comes to emissions to air, the systems with IP and stand-alone chlorine dioxide generators are the best alternatives and the system with C.I. is the worst alternative.

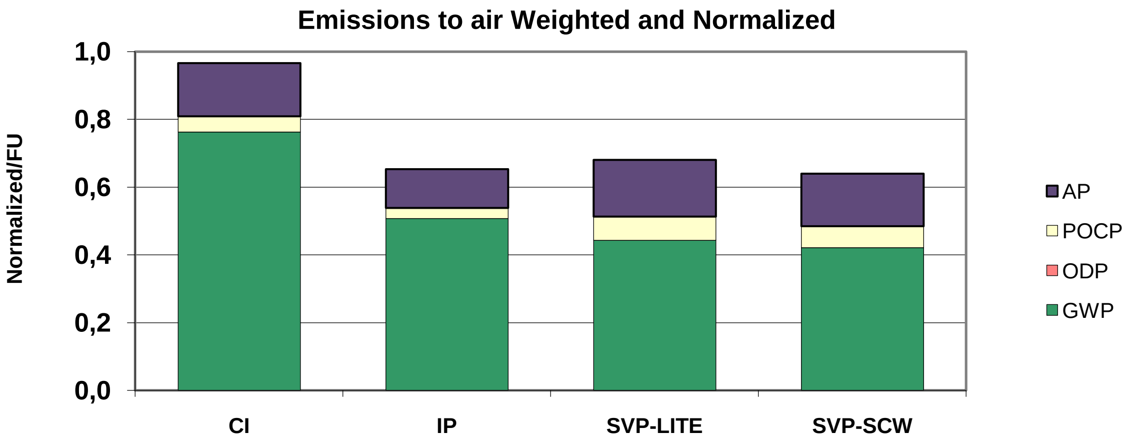

Figure 50 Weighted and normalized emissions to air, no sodium sulfate scenario.

4. Discussion

The division of the investigated system into a background system and a foreground system has multiple advantages for this study. First, it makes it possible to differentiate between the parts of the systems that are directly affected by decision making at Eka Chemicals or its customers and the parts that are not. It further makes it possible to investigate the environmental and the economic consequences of choices in control of Eka Chemicals. The results can therefore be used by Eka Chemicals in order to learn about their production systems and to create the possibility of taking sustainable strategic decisions within the studied area. The division has further made the overall LCA model more flexible to use, since the analysis can focus upon different parts of the system at a time. This approach will simplify future investigations which easily can be implemented into the existing background system. Likewise, is it possible to implement the existing foreground system into new constellations of the background system.

The division of the investigated system into a foreground and a background system combined with the methodology choice of implementing a what-if scenario analysis approach has facilitated the desire of Eka Chemicals to identify key parameters which affect the environmental performance of their production systems, e.g. geographical regional infrastructure characteristics and foreground system properties. The what-if scenario approach has further made it possible to investigate if certain expected parameters actually affect the eco-efficiency of their products. The methodology choice has made it possible to evaluate some decision based features of the production process system, in control to some extent by Eka, as well as some non decision based features in the background system. The methodological choice has made the eco-efficiency assessment flexible and this flexibility has contributed to increased knowledge of the overall system for producing bleaching chemicals used for ECF pulp.

The results from the eco-efficiency assessment show that, for the base case scenario and with the pulp mill located in Russia, the systems with chlorine dioxide generators are more eco-efficient than the systems with integrated plant and chemical island. The amounts of primary energy used by the four production systems do not differentiate and do not imply the difference in eco-efficiency between the concepts. However, the overall resource consumption for the systems with C.I. and IP is considerably higher compared to the systems with stand alone chlorine dioxide generators. This can be explained because the systems with C.I. and IP utilize a considerably higher amount of Russian electricity than the systems with SVP-LITE and SVP-SCW. The Russian electricity is mainly produced from non renewable resources and utilizing a Russian electricity mix therefore contributes to high resource consumption and especially a high consumption of non renewable resources. The impact of utilizing a Russian electricity mix can further be recognized analyzing the emissions to air from the four systems. The GWP of the systems with C.I. and IP are considerably higher than the GWPs of the systems with stand-alone chlorine dioxide generators. The reason is the higher consumption of non renewable energy resources for the systems with C.I. and IP.

The Brazilian and the biomass scenarios shows an Eco-efficiency ranking completely reversed as compared to the base case. In these scenarios, the systems with C.I. and IP are the most eco-efficient alternative followed by the systems with IP, SVP-SCW and SVP-LITE. The total primary energy use for the four production concepts is lower as compared to the base case, especially for the system with C.I. and IP. The share of renewable energy use is higher and the generation of GHG is lower in these scenarios. The weighted resource consumption is considerably lower for the systems with C.I. and IP than for the systems with stand-alone chlorine dioxide generators. This is the case since the electricity used on the pulp mill site is based mainly on renewable energy resources.

The results from the scenario analysis confirm the importance of source of electricity in order to gain a high eco-efficiency for the investigated types of process, which are highly energy demanding. The difference in Eco-efficiency between the concepts is larger in the two scenarios representing Indonesia and China compared to the base case. The ranking of the production concepts do however, not change. The GWP is the most relevant impact category regarding the emissions to air and is highest for the systems with C.I. and IP. The weighted resource consumption for Indonesia and China is higher compared to the base case and especially regarding lignite for Indonesia and coal for China. The reason is that the electricity in Indonesia and China originates from fossil fuels. The Chinese and Indonesian electricity systems consume a larger amount of non renewable resources than the Russian resulting in a higher weighted resource consumption and larger emissions of GHG.

The systems with stand-alone chlorine dioxide generators are less sensitive to changes in the background electricity systems than the systems with C.I. and IP, in terms of environmental performance. This is the case since a smaller amount of the chemicals delivered to the pulp mill are produced on-site compared to the systems with C.I. and IP. It can be concluded that a change in geographic location and electricity mix in the background system only directly affects the production of chlorine dioxide for the systems with SVP-LITE and SVP-SCW. A similar change in the background system affects the systems with C.I. and IP to a much larger extent since the major production of chemicals takes place on-site. Further on, for the systems with stand alone chlorine dioxide generators the production of sodium chlorate is performed in Sweden and Finland. Electricity generated in Sweden and Finland has a lower environmental impact compared to the Russian, Chinese, Australian and Indonesian and is one of the reasons for higher eco-efficiency of scenarios with the sodium chlorate process situated in Finland and Sweden.

Changes in the background system regarding transportation do not alter the ranking in eco-efficiency compared to the base case scenario. This can be concluded using the results from the transportation scenario. The energy consumption is less than one percent lower for all four production systems in this scenario compared to the base case scenario. However, the overall environmental impacts of the investigated systems do not change.

The eco-efficiency ranking of the systems investigated do not change in the sodium hydroxide scenario as compared to the base case scenario. There is no gain or loss in eco-efficiency in producing an increased amount of sodium hydroxide on-site compared to delivering it from production off-site. However, an environmental credit is given for the excess of chlorine which can be recovered from the chlorine alkali plant and put into the market. The environmental credit is based on mass allocation between sodium hydroxide and chlorine. If this credit not would have been given the result might have turned out differently. The result could also be expected to be different if the geographic location had been a country with an electricity mix similar to the one in Brazil or if the electricity used at the pulp mill site had been produced from biomass.

The eco-efficiency result from the no export of sodium chlorate scenario differs compared to the base case scenario. The systems with stand-alone chlorine dioxide generators are the most eco-efficient alternatives in both scenarios. However, the system with C.I. has, in the no export of sodium chlorate scenario, a higher eco-efficiency compared to the system with IP. The total primary energy use and the weighted resource consumption are considerably lower for all four production systems in this scenario compared to the base case scenario. The reason is that the annual production of sodium chlorate is decreased. It is important to notice that choosing to produce sodium chlorate for export on-site in Russia compared to producing it in Sweden or Finland actually makes the system with IP more eco-efficient compared to the system with C.I.. It can further be concluded that the systems with stand-alone chlorine dioxide generators gain a high eco-efficiency since the sodium chlorate is produced off-site and supplied to the chlorine dioxide generators located on-site. It is therefore shown that producing sodium chlorate using an electricity mix generated in the Swedish and Finnish electricity system and transporting the product to the pulp mill generates a better eco-efficiency than producing sodium chlorate on-site using Russian electricity mix.

Sending the sodium sulfate, by-product from the methanol based chlorine dioxide production processes of chlorine dioxide, to a landfill instead of using it in the pulp mill does not change the ranking in terms of eco-efficiency compared to the base case. The eco-efficiency of the IP system is improved. The reason is that the resource consumption for the system with IP because the production of sodium sulfate off-site is not required.

The environmental impact category emissions is the most relevant one, disregarding scenario studied. The emissions are categorized into emissions to air, emissions to water and solid wastes with relevancies of 72 per cent, 25 per cent and 3 per cent for the base case scenario. Since emissions to air and water are the impact categories which have a high relevance to the ranking of eco-efficiency the discussion will further focus on these impact categories.

The emissions to air can be divided into AP, POCP and GWP. The GWP is varied between the four production systems and changes significantly between the base case scenario, the no sodium sulfate scenario and the scenarios representing different electricity mixes, including the biomass scenario. Starting with the background system, the GWP is dependent on the total amount of primary energy used including the properties of the electricity-mix used in the production processes. Increasing the primary energy use and the share of fossil fuels in the power generating system results in that the GWP for the four production systems increase. The systems with C.I. and IP are the most sensitive systems to these changes. On the other hand, the GWP of these systems decreases when using an electricity mix based on renewable energy resources. The decrease is larger for the systems with C.I. and IP compared to the systems with stand-alone chlorine dioxide generators. The Brazilian electricity scenario and the biomass scenario very clearly imply this and the systems with C.I. and IP has a lower GWP compared to the systems with stand alone chlorine dioxide generators in these scenarios. The results also show that the AP and the POCP do not change significantly between different production systems and between different scenarios. The decreases vary between AP and POCP for the scenarios utilizing renewable energy as the dominant energy resource and increase for the scenarios with non renewable energy resources.

The emissions to water have a relevant contribution to the total eco-efficiency for all studied alternatives. In the base case the weighted and normalized result for emissions to water is largest for the systems with C.I. and IP. The difference between these two systems is small. For the systems with stand alone chlorine dioxide generators, the environmental impact caused by emissions to water represents 60 per cent of the corresponding impact caused by the system with C.I. and IP. The emissions of AOX from the processes have a high significance to the overall environmental impact of water emissions in the base case. The AOX emissions contribute to more than half of the weighted environmental impact caused by emissions to water.

The Brazilian electricity scenario shows a different relevance for the emissions impact categories as compared to the base case. The relevance of emissions to air is decreased and instead the relevance is increased for water emissions. The relevance factor for air emissions is explained due to that the electricity used in this scenario is mainly based on renewable energy resources and especially hydro. Hydro power does not generate much air emissions as compared to thermal power production. However, using a Brazilian electricity mix increases the water emissions of COD. The emissions can be linked to the increased use of hydro power. The COD emitted to water contributes with 40 per cent of the environmental impact caused by water emissions. This is an increase compared to the base case. The weighted emissions of AOX are not increased in this scenario compared to the base case scenario.

The resource consumption is the second most relevant impact category for the four production systems studied. The main part of the resources consumed are fossil fuels which origin from the use of electricity and steam, in processes in the foreground system as well as in the background system. Other relevant resources consumed are water, barite, copper, uranium and sodium chloride. The consumption of water is highest in the system with IP compared to the other three systems investigated. The reason is that the data used for the system with IP includes a detailed subdivision of the water consumed in the processes. It is important to highlight that data on water use often have high uncertainties and that it is difficult to assess the environmental impact of water use in LCA and keep this in mind when studying the results of resource consumption.

The consumption of uranium is higher for the systems with stand-alone chlorine dioxide generators than for the systems with C.I. and IP. This is the case since sodium chlorate is produced off-site in Alby and Oulu using electricity mixes which include a share of nuclear power. Further on, sodium chloride is a relevant resource consumed by all four production systems. It has its origin in that sodium chloride is a basic raw material used in the production process of chlorate and chlorine dioxide for all four production systems. The consumption in tonnes of sodium chloride is high in comparison to other resources. However, sodium chloride is weighted with a low weighting factor since it is not a scarce resource and the consumption is not regarded as relevant as for other resources. The reversed argumentation can be used for barite. Barite has a high relevance considering weighted resource consumption for the four production systems. It is possible to trace the use of barite to the usage of fossil fuels required for production of electricity. Therefore the relevance of barite increases with increased use of fossil fuels. However, the quantitative consumption of barite is only a couple of tons annually and represents 10 parts per million of the total resource consumption. However, since it is a scarce resource its weighting factor is high and it gets relevance for the total resource consumption of all systems.

The economic dimension is part of the eco-efficiency assessment. However, it is not possible to differentiate the production systems from each other with regard to the economic dimension using the EEA-diagram. This is the case since the annual production cost of pulp bleaching chemicals is low as compared to the environmental impact it creates. The methodology of eco-efficiency is in this case limited and the analysis should instead focus upon the environmental dimension. In order to evaluate the economic performance between the different production concepts and between the different scenarios a separate economic evaluation can be made.

Based on the discussion above and the results from the study it is possible to identify two important parameters determining the eco-efficiency for the four production concepts studied. One of the parameter is related to the background system and the other one to the foreground system.

The important parameter in the background system affecting the production systems and their eco-efficiency is the choice of geographical location and consequent electricity production mix. .Comparing the base case scenario with the different electricity scenarios and the transportation scenario it is obvious that the most important parameter determining the eco-efficiency ranking of for the production systems is the electricity mix, which is dependent on national and geographical properties. The eco-efficiency varies depending on whether the production of pulp bleaching chemicals is situated in countries using an electricity mix generated mainly from non renewable or renewable energy resources. The systems with stand-alone chlorine dioxide generators show a high eco-efficiency when the production is situated in countries where the electricity is based on non renewable energy resources. This is the case since a large share of the electricity intensive processes can be situated in countries like Sweden and Finland, utilizing a large share of renewable energy resources and nuclear power. The systems with C.I. and IP have more of their chemical production situated on-site in the country where the pulp mill is located, which includes most of the systems energy intensive processes. For background systems with electricity generated from non renewable energy resources the eco-efficiency for the systems with C.I. and IP decreases. However, utilizing electricity generated from renewable energy resources increases the eco-efficiency.

The most important parameter affecting the eco-efficiency identified in the foreground system is the choice of producing sodium chlorate on-site for the chlorine dioxide generator and export to market. Production of sodium chlorate on-site is beneficial if the electricity used on-site is based on renewable energy resources. If the electricity used in the processes is based on non renewable energy resources the benefit of producing the sodium chlorate on-site is lost.

5. Conclusions

One of the purposes with this thesis was to investigate the feasibility of building flexible LCA-models and how this can be done. The conclusion is that it is feasible to build flexible LCA models. The suggested solution is to use the background/foreground systems approach combined with what-if scenario analysis. This way it is possible to identify important parameters and assumptions that affect the overall performance of the system investigated. It further simplifies and speeds up the procedure since the assessment can be focusing on a certain part of the system at the time.

From the case study, it is concluded that with the models built and the approach with background/foreground systems combined with what-if scenario analysis, Eka Chemicals has a good platform for generating the information needed to identify the production concept with the best environmental performance for a given geographic location and site-specific conditions.

The alternative production systems studied show significant differences regarding the environmental impact dimension. When it comes to the cost dimension, it is not possible to differentiate and rank the alternative production systems by use of an eco-efficiency diagram. In order to evaluate the cost performance it is necessary to separately compare production costs, revenues, contribution margins or the costs in perspective of the customer. The reason is that when using the EEA method, the cost is related to the GDP of the region in question and the total environmental impact from the system. Since the environmental impact is weighted as more relevant in this study the cost differences therefore cannot be differentiated.

The most important conclusion of the case study is that the assumptions regarding how the electricity used for producing the bleaching chemicals, on the pulp mill site or elsewhere, are crucial for the ranking of the production systems compared. Whether or not electricity produced from biomass in the pulp mill can be bought and used for production of chlorine dioxide and other chemicals on the pulp mill site is extremely important. The production of sodium chlorate is very energy intensive and thus the electricity mix used in this process is a key assumption.

For the specific pulp mill in Russia, using the assumptions described, it is concluded that:

- The most eco-efficient alternative when electricity is sourced from the national Russian grid is a SVP-SCW chlorine dioxide generator. Second best and very close in environmental performance is the SVP-LITE chlorine dioxide generator. The integrated plant and the chemical island are ranked third and fourth place, respectively. Both alternatives are significantly worse in terms of environmental performance as compared to the stand alone chlorine dioxide generators.
- The ranking in terms of eco-efficiency would be reversed if electricity produced from biomass is used when producing chemicals on the pulp mill site. If so, the chemical island would be the most eco-efficient alternative. Integrated plant would be second best and stand alone chlorine dioxide generators the least eco-efficient alternatives (SVP-SCW somewhat better than SVP-LITE).

From the background system analysis, using the assumptions as described, it is concluded that:

- The geographical location of the production of ECF-pulp bleaching chemicals is a key parameter when trying to find the most eco-efficient production concept.
- The chemical island and integrated plant systems score well in terms of eco-efficiency when utilizing an electricity mix based on a high share of renewable energy resources. However, the systems with SVP-SCW and SVP-LITE are to prefer when utilizing an electricity mix based on non renewable energy resources and if sodium chlorate produced with a low carbon electricity mix can be sourced.

- With the pulp mill located in Brazil and electricity from the national grid for production of chemicals on the pulp mill site, the ranking (environmental impact) of the compared production systems is (1, best) chemical island; (2) integrated plant; (3) SVP-SCW; and (4, worst) SVP-LITE.
- With the pulp mill located in China or Indonesia and electricity from the national grid for production of chemicals on the pulp mill site, the ranking (environmental impact) of the compared production systems is (1, best) SVP-SCW; (2) SVP-LITE; (3) integrated plant; and (4, worst) chemical island.
- The properties of the transportation system (distances and mode of transportation) connected to the production of ECF-pulp bleaching chemicals have a small influence on the environmental performance of the system.

Assuming electricity from the national Russian grid is used to produce chemicals on the pulp mill site, the following can, using the assumptions as described, be concluded from the foreground system analysis:

- The eco-efficiency ranking is not dependent on whether or not all sodium hydroxide is produced on-site in the system with integrated plant.
- Whether or not export of sodium chlorate is included in the basis of comparison influences the eco-efficiency ranking of the compared production concepts. Dimensioning the chemical island so that only the amount of sodium chlorate needed to produce the pulp mill demand for chlorine dioxide results in the chemical island system becoming more eco-efficient than the integrated plant system. The systems with stand-alone chlorine dioxide generators remain the most eco-efficient alternatives. Further, the choice of producing sodium chlorate on the pulp mill site using an electricity mix generated from fossil fuels has an environmental drawback compared to producing the same amount of sodium chlorate off-site using an electricity mix representing Sweden or Finland.
- The pulp mill demand for sodium sulfate is a key parameter for the environmental impact caused by the integrated plant system. Assuming no demand at all for sodium sulfate results in the eco-efficiency of the integrated plant coming very close to the eco-efficiency of the stand alone chlorine dioxide generators. The ranking of the compared production systems in terms of eco-efficiency, however, remain unchanged.

The most relevant environmental impact categories when producing pulp bleaching chemicals for ECF-pulp production are emissions followed by resource consumption. Further, the emissions to air, and more specifically the greenhouse gases, are the most relevant impact category among emissions. Among the natural resources consumed, the fossil fuels are the most relevant for all four production systems investigated.

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