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Laura Sokka

Local systems, global impacts

Using life cycle assessment to analyse the potential and constraints of industrial symbioses

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Faculty of Biological and Environmental Sciences
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Academic dissertation

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Abstract

Human activities extract and displace different substances and materials from the earth’s crust, thus causing various environmental problems, such as climate change, acidification and eutrophication. As problems have become more complicated, more holistic measures that consider the origins and sources of pollutants have been called for.

Industrial ecology is a field of science that forms a comprehensive framework for studying the interactions between the modern technological society and the environment. Industrial ecology considers humans and their technologies to be part of the natural environment, not separate from it. Industrial operations form natural systems that must also function as such within the constraints set by the biosphere. Industrial symbiosis (IS) is a central concept of industrial ecology. Industrial symbiosis studies look at the physical flows of materials and energy in local industrial systems. In an ideal IS, waste material and energy are exchanged by the actors of the system, thereby reducing the consumption of virgin material and energy inputs and the generation of waste and emissions. Companies are seen as part of the chains of suppliers and consumers that resemble those of natural ecosystems.

The aim of this study was to analyse the environmental performance of an industrial symbiosis based on pulp and paper production, taking into account life cycle impacts as well. Life Cycle Assessment (LCA) is a tool for quantitatively and systematically evaluating the environmental aspects of a product, technology or service throughout its whole life cycle. Moreover, the Natural Step Sustainability Principles formed a conceptual framework for assessing the environmental performance of the case study symbiosis (*Paper I*). The environmental performance of the case study symbiosis was compared to four counterfactual reference scenarios in which the actors of the symbiosis operated on their own. The research methods used were process-based life cycle assessment (LCA)

(*Papers II* and *III*) and hybrid LCA, which combines both process and input-output LCA (*Paper IV*).

The results showed that the environmental impacts caused by the extraction and processing of the materials and the energy used by the symbiosis were considerable. If only the direct emissions and resource use of the symbiosis had been considered, less than half of the total environmental impacts of the system would have been taken into account. When the results were compared with the counterfactual reference scenarios, the net environmental impacts of the symbiosis were smaller than those of the reference scenarios. The reduction in environmental impacts was mainly due to changes in the way energy was produced. However, the results are sensitive to the way the reference scenarios are defined.

LCA is a useful tool for assessing the overall environmental performance of industrial symbioses. It is recommended that in addition to the direct effects, the upstream impacts should be taken into account as well when assessing the environmental performance of industrial symbioses. Industrial symbiosis should be seen as part of the process of improving the environmental performance of a system. In some cases, it may be more efficient, from an environmental point of view, to focus on supply chain management instead.

Laura Sokka. Local systems, global impacts. Using life cycle assessment to analyse the potential and constraints of industrial symbioses [Paikalliset systeemit – globaalit vaikutukset. Elinkaariarviointi teollisen symbioosin arvioinnissa]. Espoo 2011. VTT Publications 768. 71 s. + liitt. 76 s.

Asiasanat industrial ecology, industrial symbiosis, pulp and paper industry, life cycle assessment, case study, Natural Step System Conditions, Finland

Tiivistelmä

Ihminen louhii ja siirtää erilaisia aineita ja materiaaleja maaperästä aiheuttaen samalla monia ympäristöongelmia, kuten ilmaston lämpenemistä, happamoitumista ja rehevöitymistä. Ongelmien tullessa monimutkaisemmiksi on syntynyt tarve kokonaisvaltaisemmille menetelmille, jotka huomioivat saasteiden lähteen.

Teollinen ekologia on tieteenala, joka tarjoaa kokonaisvaltaisen viitekehyksen modernin teknologisen yhteiskunnan ja ympäristön välisen vuorovaikutuksen tutkimiseen. Teollisessa ekologiassa yhteiskunnan ajatellaan olevan osa luonnonympäristöä eikä erillinen siitä. Teollinen toiminta muodostaa luonnon systeemejä, joiden on toimittava biosfäärin asettamissa rajoissa. Keskeinen käsite teollisessa ekologiassa on teollinen symbioosi. Teollinen symbioosi tutkii materiaalin ja energian virtoja paikallisissa systeemeissä. Ihanteellisessa teollisessa symbioosissa symbioosin toimijat vaihtavat materiaaleja ja energiaa keskenään ja vähentävät siten päästöjä ja jätteitä. Yritykset nähdään kuluttajien ja tuottajien verkostona, joka muistuttaa luonnon ekosysteemiä.

Tämän tutkimuksen tavoitteena oli analysoida sellu- ja paperintuotantoon perustuvan teollisen symbioosin ympäristövaikutuksia huomioiden koko elinkaari. Elinkaariarviointi on menetelmä, jolla voidaan arvioida tietyn tuotteen, teknologian tai palvelun koko elinkaaren aikaiset ympäristövaikutukset. Natural Step -kestävyysperiaatteet muodostivat käsitteellisen viitekehyksen tutkimuskohteena olevan symbioosin ympäristövaikutusten arviointiin (osajulkaisu I). Tapaustutkimussymbioosin ympäristövaikutuksia verrattiin neljään teoreettiseen referenssiskenaarioon, joissa symbioosin toimijat toimivat erillään. Käytetyt tutkimusmenetelmät olivat niin sanottu prosessielinkaariarviointi (osajulkaisut II ja III) ja hybridielinkaariarviointi (osajulkaisu IV).

Tulokset osoittavat, että symbioosin käyttämien raaka-aineiden louhinnan ja prosessoinnin sekä energian tuotannon ympäristövaikutukset olivat huomattavia.

Jos vain suorat päästöt ja raaka-aineiden kulutus olisi huomioitu, yli puolet symbioosin kokonaisympäristövaikutuksista olisi jäänyt huomioimatta. Kun tuloksia verrattiin referenssiskenaarioihin, voitiin todeta, että symbioosin nettoympäristövaikutukset olivat kaikissa vaikutusluokissa referenssiskenaarioita pienemmät. Tämä johtui pääasiassa energiantuotannosta. Tulokset ovat kuitenkin herkkiä sille, miten vertailuskenaariot määritellään.

LCA on hyödyllinen väline teollisten symbioosien kokonaisympäristövaikutusten arviointiin. Raaka-aineiden ja energian tuotannon ympäristövaikutukset tulisi huomioida, kun arvioidaan teollisen symbioosin kokonaisympäristövaikutuksia. Teollinen symbioosi tulisi nähdä yhtenä osana systeemin ympäristövaikutusten hallintaa. Joissakin tilanteissa saattaa olla ympäristön kannalta tehokkaampaa keskittyä hankintaketjun hallintaan teollisen symbioosin sijaan.

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Contents

Appendices

List of original publications and authors' contribution

I **Sokka, L.**, Melanen, M. & Nissinen, A. 2008. How can the sustainability of industrial symbioses be measured? In: Progress in Industrial Ecology – An International Journal 5(5–6): 518–535.

II **Sokka, L.**, Pakarinen, S. & Melanen, M. 2011. Industrial symbiosis contributing to more sustainable energy use – an example from the forest industry in Kymenlaakso, Finland. In: Journal of Cleaner Production 19(4): 285–293.

III **Sokka, L.**, Pakarinen, S., Nissinen, A. & Melanen, M. 2011. Analyzing the Environmental Benefits of an Industrial Symbiosis – Life Cycle Assessment (LCA) Applied to a Finnish Forest Industry Complex. In: Journal of Industrial Ecology 15(1): 137–155.

IV Mattila, T.J., Pakarinen, S. & **Sokka, L.** 2010. Quantifying the total environmental impacts of an industrial symbiosis – a comparison of process-, hybrid and input–output life cycle assessment. In: Environmental Science and Technology 44(11): 4309–4314.

In *Paper I* Laura Sokka is the corresponding author. The manuscript was jointly written by Laura Sokka and Matti Melanen. Ari Nissinen commented on the manuscript.

In *Papers II and III* Laura Sokka is the corresponding author. Data were collected and analysed by Laura Sokka and Suvi Pakarinen. Laura Sokka was responsible for writing the manuscripts while Matti Melanen supervised the study and commented on the manuscripts. Suvi Pakarinen commented on both manuscripts and Ari Nissinen commented on manuscript III.

Paper IV was jointly planned by Tuomas Mattila and Laura Sokka. The data collection and the process life cycle inventory (LCI) analysis were conducted by

Laura Sokka and Suvi Pakarinen. Tuomas Mattila conducted the hybrid and input-output LCI analysis and life cycle impact assessment. Tuomas Mattila wrote the manuscript. Laura Sokka and Suvi Pakarinen played an essential role as commentators on the manuscript.

1. Introduction

Human actions have increasingly changed the environment since the beginning of the Industrial Revolution and even more so after the Second World War. For example, different substances and materials are extracted and displaced through human actions, thereby causing various environmental problems such as eutrophication, acidification and spreading of toxic substances. In recent years, climate change has increasingly been recognised as an important topic. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) further confirmed the anthropogenic impact on global warming [Solomon et al. 2007]. Energy-related issues and the reduction of greenhouse gas (GHG) emissions are being more and more emphasised in environmental policy both nationally and internationally.

The Millennium Ecosystem Assessment (MA) was conducted between 2001 and 2005 to examine the consequences of changes in ecosystems for human welfare [Millennium Ecosystem Assessment 2005]. The assessment was set to respond to government requests for information through four different international conventions: the Convention on Biological Diversity, the United Nations Convention to Combat Desertification, the Ramsar Convention on Wetlands and the Convention on Migratory Species. In brief, the assessment ended in a warning: human activities are straining the natural functions of the earth in such a way that the ability of the planet's ecosystems to sustain future generations is threatened. The most pressing problems identified in the assessment included the increasing threat posed by climate change and increased nutrient flows to ecosystems; the vulnerability of the two billion people who live in dry regions to the loss of ecosystem services, such as water supply; and the decline in the world's fish stocks.

For decades, environmental protection focused on point source control of emissions. As problems have become more complicated, it has been realised that more holistic measures that consider the origins and fates of pollutants are also needed. More recently, integrated pollution prevention and control (IPPC) has become a primary principle of environmental protection policies. When IPPC is followed, resource use and emissions to water, air and soil are controlled and reduced simultaneously. Life Cycle Assessment (LCA) is a tool for quantitatively and systematically evaluating the environmental aspects of a product or system throughout its whole life cycle [Rebitzer et al. 2004, Finnveden et al. 2009]. Comprehensive tools, such as LCA, that concentrate on all the inflows and outflows of substances in a certain system provide means to identify effective policy options. Such knowledge also reduces the risk of simply shifting pollution from one environmental media to another. LCA has primarily been applied to assess the life cycle impacts of products but it can also be used for the assessment of services, technologies or regions [Hendrickson et al. 2006, Lenzen et al. 2003, Payraudeau & van der Werf 2005, Eriksson et al. 2007, Yi et al. 2007].

1.1 Industrial ecology and industrial symbiosis

The field of industrial ecology forms a comprehensive framework for studying the interactions between the modern technological society and the environment [Harper & Graedel 2004, Jelinski et al. 1992]. It aims to minimise inefficiencies and the amount of waste created in the economy. Industrial ecology analyses the flows of materials and energy of industrial activities, including the effects of these flows on the environment, as well as the influence of economic, political, regulatory and social factors on the use, transformation and disposition of resources [Diwekar 2005]. A key idea of industrial ecology is that processes and industries are seen as interacting systems, not isolated parts of a system with linear flows [Gibbs & Deutz 2007]. Industrial ecology argues for a wider view that considers humans and their technologies as part of the environment, not separate from it. Industrial operations are natural systems that must also function as such within the constraints set by the biosphere [Lowe & Evans 1995].

The expression ‘industrial ecology’ first started appearing in the literature in the 1970s, but the ideas behind it existed long before that [Erkman 2001]. The article by Frosch and Gallopoulos that appeared in the *Scientific American* in 1989 is usually considered the beginning of industrial ecology in its present form [Gibbs & Deutz 2007]. The paper presented the basic principles of industrial ecology [Frosch & Gallopoulos 1989]. The authors called for a change from traditional industrial systems to industrial ecosystems where the use of energy and materials is optimised, waste generation is minimised and the remnants of one process are used as raw materials of another.

Industrial ecology can be studied at three different levels [Chertow 2000]: a facility level, the inter-firm level and the regional or global level. Industrial symbiosis, which has become a key concept within industrial ecology, represents analysis at the inter-firm level [Lowe & Evans 1995]. In industrial symbioses, also referred to as eco-industrial parks or industrial ecosystems, companies and other economic actors form networks of suppliers and consumers [Gibbs & Deutz 2007]. The concept of symbiosis is derived from the notion of symbiotic relationships in the natural environment in which unrelated species exchange energy and materials in a mutually beneficial way [Chertow 2000]. In order to survive and maintain their productivity, these actors rely on resources that are available in the natural environment. Studies of industrial symbioses primarily concern the recovery and reuse of wastes from one facility as an input to a neighbouring industry [van Berkel 2009]. In an ideal industrial symbiosis, waste materials and energy are utilised between the actors of the system, thus reducing the consumption of virgin material and energy inputs and the generation of waste and emissions [Chertow 2000].

Industrial symbioses are usually initiated by economic gains between individual actors: resource sharing may reduce costs or increase revenues. An industrial symbiosis may also be motivated by, for example, long-term resource security, and it can enhance the availability of water, energy or other raw materials [Chertow 2007]. The actors start to exchange excess material and energy side-streams between one another, thereby forming an ‘industrial symbiosis’. One feature of these systems is that they often evolve in space and over time [e.g. Korhonen & Snäkin 2005, Pakarinen et al. 2010]. Chertow [2007] has developed a minimum criterion for what constitutes an industrial symbiosis: at least three different entities are involved in exchanging at least two different materials, products or other resources. None of the participating three entities should primarily be a recycling-oriented business.

During recent years, at least 50 examples of industrial symbioses have been described in the literature [van Berkel 2009]. Industrial symbioses can either develop spontaneously or be purposely designed as such. Perhaps the best known and most quoted example of spontaneously evolved symbioses is the Kalundborg industrial symbiosis in Denmark [Lowe & Evans 1995, Chertow 2000, Jacobsen 2006]. Designed eco-industrial parks have been analysed by, for example, Gibbs and Deutz [2007]. However, only fairly few studies have attempted to quantify the environmental (or sustainability) performance of IS networks to date. One example of such a study is Chertow and Lombardi [2005] who quantified the economic and environmental costs and advantages for the partners of a symbiosis network in Puerto Rico. The study concluded that the participating organisations receive substantial economic and environmental benefits from participating in the symbiosis but that the benefits are unevenly distributed. According to the authors, it is likely that similar benefits are also found in other comparable situations. Further examples of studies that have assessed the environmental benefits of industrial symbioses include Jacobsen [2006], Salmi [2007], Wolf and Karlsson [2008], Beyene [2005], van Berkel [2009], Korhonen and Snäkin [2005], and Singh et al. [2007].

All of the studies mentioned above concentrate on the direct impacts of the symbioses, however, thereby ignoring upstream and downstream impacts. So far, only a few studies have attempted to quantify the life cycle environmental impacts of industrial symbioses. One example is the study conducted by Sendra et al. [2007] in which material flow analysis (MFA) methodology was applied to an industrial area in Spain. In this study, MFA-based indicators were combined with additional water and energy indicators to assess how the area could be developed into an eco-industrial park. Thus, the study had a life cycle view but it did not include an impact assessment. In a more recent study, Eckelman and Chertow [2009] analysed the industrial waste production in the State of Pennsylvania. In the study, the authors combined waste data from the state with life cycle inventory data in order to calculate the current and potential environmental benefits of utilising this waste. According to the results, the reuse of the studied waste streams had positive environmental impacts compared to the use of the substituted material in almost all the cases. One exception was the replacement of heavy fuel oil with waste oil because waste oil had higher SO_2 emissions than heavy fuel oil.

Uihlein and Schebek [2009] compared the environmental impacts of a lingo-cellulosic feedstock biorefinery with the production of fossil alternatives using LCA. The system was not considered an IS, but it operates similarly in practice. As the lingo-cellulosic feedstock biorefinery has not yet been implemented in practice, the authors studied three different configurations of the concept. The results indicated that for all the studied options, the environmental performance of the biorefinery was superior to the corresponding fossil production options in some impact categories and inferior in other impact categories. Nevertheless, in terms of the overall results, it was concluded that from an environmental point of view, the lingo-cellulose biorefinery concept could be superior to the existing fossil production options [Uihlein & Schebek 2009].

Thus, numerous examples of industrial symbioses or eco-industrial parks have been presented in the literature. When discussing industrial symbioses or eco-industrial parks, it is usually assumed that increasing the local utilisation of material and energy flows will necessarily benefit the environment. As the above review shows, most studies have focused on the impacts within the boundaries of the symbiosis and thereby excluded upstream and downstream impacts. However, only a few assessments to date have been comprehensive enough to determine whether industrial symbioses actually provide environmental benefits.

1.2 Study area: a forest-industry-based industrial symbiosis in Finland

Over 60% of the Finnish land area is covered by forests, and forest industry has traditionally been a very important sector in the country. In 2007, approximately 14% of the total industrial added value originated from pulp and paper production and approximately 5% from the manufacture of wood products [Statistics Finland 2010c]. The share of exports in paper and paperboard production is very high: about 90% in 2008 [Peltola et al. 2009]. Altogether, approximately 17% of the total value of Finnish exports came from pulp and paper production and the manufacture of wood products in the same year. The most important destination countries were Germany and the UK [Peltola et al. 2009].

In this study, a forest-industry-based industrial symbiosis situated in the highly industrialised Kymenlaakso Region in Finland was used as a case study. Kymenlaakso is located in South-eastern Finland, next to the Russian border. As a consequence of its location and industrial structure, the Kymenlaakso region has strong trade links to the national and global economic system. It has a strong pulp and paper industry, which makes up the core of its business economy. The share of pulp and paper production of the total value added of the region was 12% in 2007 [Statistics Finland 2010c].

During the past few years, however, the pulp and paper industry has been undergoing a major structural change. As a result, several production units have been closed down. Permanent cuts in production have reduced the total pulp and paper capacity by almost 20% since the beginning of 2007 [Reini et al. 2010]. Kymenlaakso Region has been hit particularly hard by the cuts. Reini et al. [2010] have estimated that the cuts in production announced by the beginning of

2010 will cumulatively reduce the economic growth of the region by 7% between 2010 and 2013. New solutions for the future development of the industry are being sought from the so-called biorefineries in which biomass conversion processes are integrated in order to produce chemicals, fuels, power and heat from biomass [e.g., Kamm & Kamm 2004, Uihlein & Schebek 2009, see also Mäkinen & Leppälahti 2009]. Such biorefineries operate similarly to industrial symbioses.

Pulp and paper production consumes a large amount of energy, particularly electricity. In 2007, it used 31% of the total electricity consumption in Finland [Statistics Finland 2008]. However, due to the considerable use of renewable fuels, such as bark and black liquor, the fuel-based fossil GHG emissions of the sector made up less than 10% of the total Finnish emissions in 2008 [Peltola 2009]. Altogether, wood-based fuels constitute approximately 20% of the total energy use in Finland [Statistics Finland 2008].

It is typical of the Scandinavian forest industry to operate as an ‘industrial symbiosis’, and many case studies have addressed this [e.g., Korhonen 2001, Korhonen et al. 2001, Wolf & Karlsson 2008]. Pulp and paper mills often form local industrial systems, which, besides the pulp and/or paper mill itself, include, for example, a power plant, chemical manufacturing plants, waste management facilities and sewage treatment plants. In addition, a local municipality may be connected to the system through district heat and electricity supply from a combined heat and power (CHP) plant [Korhonen et al. 2001]. As operation as an industrial symbiosis is so common in the forest industry some may even argue that these forest industry systems do not qualify as an industrial symbiosis. The idea behind this argument is that only systems that have intentionally been developed as industrial symbioses or eco-industrial parks form an industrial symbiosis. However, many authors have also considered systems that have spontaneously evolved as industrial symbioses. Taking, for example, the minimum criterion presented by Chertow [2007, see Section 1.1] as a starting point, the by-product linkages that exist within the forest industry systems usually form an industrial symbiosis.

2. Objective of the study

The objective of this study is to analyse the environmental life cycle impacts of an industrial symbiosis based on pulp and paper production. In addition, the overall environmental performance of the case study symbiosis is compared with four counterfactual reference scenarios in which the actors work on their own. The specific research questions of this study are:

1. What are the overall life cycle environmental impacts of an industrial symbiosis?
2. What is the magnitude of the emissions from upstream processes compared to that of the direct emissions of the system?
3. Does industrial symbiosis produce environmental benefits compared to systems where companies work on their own?
4. What is the role of local systems, such as industrial symbioses, in enhancing global environmental sustainability?

The questions are addressed through a case study symbiosis based on pulp and paper production. *Paper I* first introduces the symbiosis case study (hereafter referred to as the IS Case). Previous studies that quantify the environmental benefits of industrial symbioses are then reviewed. Moreover, it is suggested that the Natural Step System Conditions could be used as a basis for assessing the sustainability of industrial symbioses. In *Paper II* the greenhouse gas emissions and energy use of the IS Case are studied. In addition, the system is compared to two counterfactual reference scenarios in which the actors of the symbiosis operate in a stand-alone mode. In *Paper III*, the analysis of *Paper II* is extended to include other environmental impacts, and the operation of the system is compared to other two counterfactual stand-alone scenarios. In *Paper IV*, hybrid LCA, which combines ‘traditional’, process-based LCA with an input-output LCA, is carried out and the findings are compared to results from *Paper III*. The relevance of cut-off in process-based LCA and the resulting implications for the assessment of industrial symbioses are discussed.

3. Material and methods

3.1 Case study symbiosis

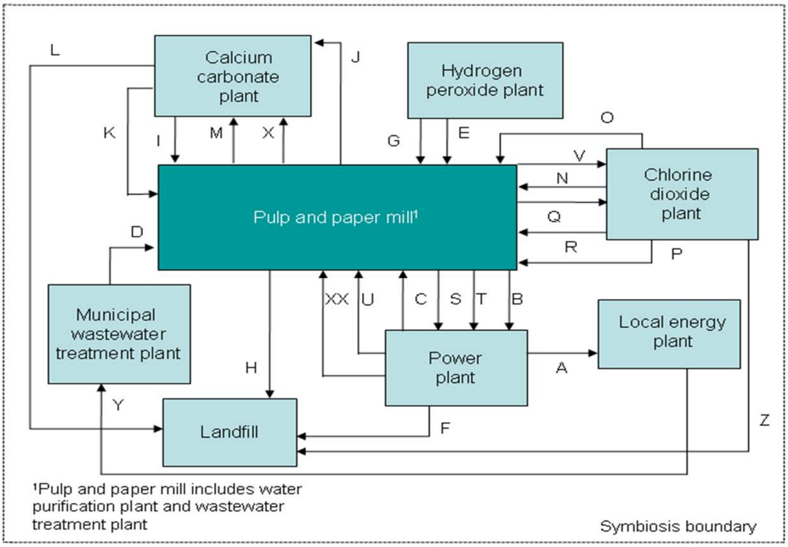
The IS Case of *Papers I–IV* is based on pulp and paper production. The system has spontaneously evolved around an integrated pulp and paper manufacturer, the Kymi mill of the UPM Kymmene Corporation (Fig. 1). Paper production began at the site back in 1874. Thirty years later, there were three separate pulp and paper mills at the site. The plants merged in 1904 in order to gain a competitive advantage. The current Kymi plant represents two of these plants. The third one was excluded from this study, as it was later closed down. Chemical production started at the beginning of the 20th century when a sodium hypochlorite plant was founded [Tuuri 1999]. Some 20 years later, chlorine lime production for pulp bleaching was begun. The hydrogen peroxide plant was founded in 1972 [Talvi 1972]. At the time, the pulp and paper mill also owned the chemical production facilities. Only later was the ownership separated and, at present, even the power plant is only partly owned by the pulp and paper mill. The evolution of the case study symbiosis has been discussed more extensively by Sokka et al. [2009] and Pakarinen et al. [2010].

Since the early stages of the park's evolution, it has cooperated with the local community. In other words, the plant has been an important actor in the area. For example, the plant took care of the municipality's electricity needs up until the 1950s [see Pakarinen et al. 2010]. In 1872, when the first pulp and paper mills were founded, there were mills on both sides of the River Kymi. When the plants bought rapids rights they allowed the farmers to use the water mills for free. In the late 1970s, the farmers continued to use these mills. As early as 1921, the plant started fish farming to compensate for the damage caused by the dam. The plants also offered apartments for employees and built schools for children in the area.

The number of actors in the system and the connections between these actors, as well as the size of the production and the diversity of products, have increased continuously. At the end of the 1980s, the chlorine plant began selling hydrogen gas to the hydrogen peroxide plant, marking the start of a more symbiotic operation between the actors [Sokka et al. 2009].

In addition to the pulp and paper mill, the system currently includes a power plant, three chemical plants (a chlorine dioxide plant, a calcium carbonate plant and a hydrogen peroxide plant), a municipal sewage plant, local energy distributor and a landfill site. The power plant uses wood residues and sludge from the pulp and paper mill as fuel (Fig. 1). The power plant then sells steam, electricity and heat to the pulp and paper mill, which in turn provides electricity and heat to the chemical manufacturers. The power plant also provides electricity and district heat to the nearby town of Kouvola (distributed by the local energy plant). Besides providing chemicals to the pulp and paper mill, the chlorine dioxide and the calcium carbonate plants receive energy and chemically purified water from the pulp and paper mill. The calcium carbonate plant also uses carbon dioxide from the flue gases of the pulp and paper mill as raw material. The municipal sewage plant delivers part of its sewage sludge to the wastewater treatment plant of the pulp and paper mill where its nutrients reduce the need to add urea and phosphoric acid to the wastewater treatment process. In addition, the pulp and paper mill takes care of the waste management of the power plant, calcium carbonate plant and chlorine dioxide plant.

In the following, the different actors of the symbiosis are described in more detail. For the text, environmental permits of the respective company have been used as a reference unless otherwise stated.



A	District heat and electricity	N	Chlorine (Cl_2)
B	Sewage sludge	O	Wastewater
C	Wastewater	P	Chlorine dioxide (ClO_2)
D	Sewage sludge	Q	Water
E	Wastewater	R	Sodium hydroxide (NaOH)
F	Ash	S	Sodium hydroxide (NaOH)
G	Hydrogen peroxide (H_2O_2)	T	Biomaterials used as fuel
H	Miscellaneous inert waste	U	Steam, electricity, heat
I	Wastewater	V	Steam
J	Water	X	Steam and electricity
K	Calcium carbonate (CaCO3)	Y	Electricity
L	Miscellaneous waste	Z	Waste
M	Carbon dioxide (CO_2)	XX	Water

Figure 1. Actors of the IS Case and the flows of materials and energy between them. The dashed line represents the boundary of the symbiosis. (Modified from *Paper I*)

Pulp and paper plant

The pulp and paper mill represents integrated pulp and paper production. The integration produced 530,000 tonnes of pulp and 840,000 tonnes of paper in 2005. Approximately 55% of the wood used by the UPM Kymi mill is hardwood, i.e. birch, and the rest is softwood, i.e. pine and spruce. The plant produces higher quality paper, i.e., coated and uncoated fine paper, which typically contains approximately 20–25% fillers [Hart et al. 2005], such as kaolin and starches. Minerals therefore form an important production input.

Most of the pulp produced is used on site at the paper mill. Only a small fraction is sold to other paper mills of UPM. The pulp mill has two production lines: one line uses hardwood as its raw material and the other softwood. Pulp production at the present sulphate pulp plant began in 1964. Part of the production equipment still dates back to 1964. It has gradually been renewed in 1977, 1999 and 2002. In 2008, a new pulp recovery line was constructed that replaced the former chemical recovery lines (still in use in 2005).

The paper mill is divided into two production units. Paper machine 8 and coating machine 3 constitute a coated fine paper production line. Paper machine 9 produces uncoated fine paper on reels and in sheets (UPM, Kymi Environmental Performance in 2008). The energy production of the mill stems from black liquor and from the Kymin Voima steam power plant. In addition there is a natural gas boiler and a boiler for odorous gases, which act as back-up power sources. The integration is self-sufficient as concerns heat. Half of the electricity requirement is purchased from UPM Energy.

Power plant

The Kymin Voima power plant started operation in 2002. The plant is a 295 MW combined heat and power plant. The electricity production capacity of the plant is 85 MW. The production capacities of process steam and district heat are 125 MW and 60 MW, respectively. The plant has a bubbling fluidised bed boiler. Most of the steam and heat produced by the power plant are used at the pulp and paper mill. The plant also produces district heat for the Kuusankoski and Kouvola towns. The power plant is mainly fuelled by bark, sludge and sawdust received from the pulp and paper mill and other forest industry in the region. Peat and natural gas are used as supplementary fuels.

Calcium carbonate plant

The calcium carbonate plant produces four different products that are used as fillers in fine paper and SC paper production. The capacity of the plant is 170,000 tonnes of dry calcium carbonate per year. The main raw material of the plant is calcium oxide, which is carbonated with carbon dioxide into calcium carbonate. The carbon dioxide stems from the flue gas of the pulp mill. The electricity and heat used by the plant are also received from the pulp and paper mill. Approximately 75% of the production of the plant is used at the UPM Kymi plant.

Chlorine dioxide plant

The plant started operation in 1990. The maximum production capacity of chlorine dioxide is 14,000 tonnes per year. The annual production has varied between 6,000 and 10,000. All of the production is used as a bleaching chemical in pulp production on site. The product is handled as mild water solution and is delivered through a pipe to the pulp mill. Chlorine dioxide is produced with an integrated method using hydrochloric acid (HCl). The production process consists of chlorate electrolysis, and the production of hydrochloric acid and chlorine dioxide.

In addition to chlorine dioxide, the plant produces approximately 2,500 tonnes of 2-ethylhexanoic acid annually, which is used as a wood preservative. The raw materials of 2-ethylhexanoic acid are liquid coco alkyl trimethyl ammoniumchloride, 2-ethyl hexanic acid and sodium hydroxide, and solid borax. The plant also transmits sodium hydroxide and chlorine, some of which is used in its own production and the rest of which is delivered to the pulp and paper mill.

The integrated production process is energy efficient and the energy use of the plant is therefore fairly low. The heat and electricity used by the plant are received from the pulp and paper mill.

Local energy plant[1]

The KSS Energia energy plant supplies electricity and heat to the nearby town of Kouvola. It produces 85% of the district heat used in the region. The company owns 24% of the Kymin Voima power plant directly and also has a share of the Pohjolan Voima Oy, which is the other owner of Kymin Voima. KSS Energia

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[1] Source: http://www.kssenergia.fi/kss-energia/sahkon-tuotanto.

receives approximately 250 GWh of heat from the Kymin Voima power plant annually. This represents approximately two thirds of the district heat consumption of Kouvola. In addition to Kymin Voima, KSS Energia has four other power plants: the Hinkismäki natural gas power plant and three hydropower plants. The company also owns part of the Norwegian Rana hydropower plant. The Hinkismäki natural gas power plant is a peak-load power plant with a maximum fuel power of 140 MW. It is mainly operated during the cold winter months.

Hydrogen peroxide plant

The hydrogen peroxide plant is the only one of the chemical production plants of the IS Case that is not located at the Kymi mill site. Instead, it is located at the site of the former Voikkaa paper mill, which has been closed down. Despite this, the hydrogen peroxide plant is considered part of the symbiosis because it has close cooperation with the Kymi pulp and paper mill.

Production of hydrogen peroxide (H_2O_2) at the site began in the 1970s. The old hydrogen peroxide production line from the 1970s and the hydrogen plants from the 1980s and 1990s have gradually been replaced during the past few years with the opening of a new production line. In addition to H_2O_2, the plant produces $C_2H_4O_3$. In the new factory, the production capacity is 85,000 tonnes of H_2O_2. H_2O_2 is produced from hydrogen and oxygen, which is retrieved from the air. Hydrogen is produced from natural gas and water vapour. $C_2H_4O_3$ is produced from hydrogen peroxide and acetic acid. The main energy source of the plant is natural gas. Steam is also produced from the waste heat of the production process. Additional electricity and steam are purchased from the markets.

Municipal wastewater treatment plant

The municipal wastewater treatment plant delivers its sewage sludge to the wastewater treatment plant of the pulp and paper mill where it reduces the need to add nitrogen and phosphorus to the treatment process. The municipal wastewater treatment plant treats the wastewaters of Kouvola town. Most of the wastewater is municipal, but the plant also treats some industrial wastewater. The average flow of the plant was 13,800 m^3 in 2004. In addition, it treated 4,400–6,100 m^3 sedimentation basin sludge annually between 1999 and 2004.

3.2 The Natural Step System Conditions

The concept of sustainable development and the ways in which it can be achieved have been addressed by several different studies and initiatives. One of these is the Natural Step System Conditions, also known as the sustainability principles, introduced by Karl-Henrik Robèrt and his colleagues [e.g., Holmberg & Robèrt 2000, Robèrt 2000, Robèrt et al. 2002, Ny et al. 2006, see also *Paper I*]. The key idea of the principles is that rather than agreeing on detailed descriptions of a desirable future, it would be easier to agree on the basic principles for sustainability [Ny et al. 2006].

Within the Natural Step context, four system conditions for ecological and social sustainability were formulated [Robèrt et al. 2002]:

> *In sustainable society, Nature is not subject to systematically increasing:*
>
> *I concentrations of substances extracted from the Earth's crust;*
> *II concentrations of substances produced by society; or*
> *III degradation by physical means.*

In addition, the system condition for social sustainability requires that in that society:

> *IV people are not subject to conditions that systematically undermine their capacity to meet their human needs.*

The Natural Step System Conditions are based on back-casting: envisioning a desired outcome and making step-by-step plans on how to achieve it [Holmberg & Robèrt 2000]. The approach is very different from, perhaps, the prevailing approach, which focuses on the short-term effects and problems of different alternatives and forgets the ultimate goal of the planning, such as sustainability. It is argued that these sustainability principles can complement some of the existing tools for measuring sustainability (such as LCA) by informing and introducing a sustainability perspective to them [e.g., Robèrt et al. 2002, Ny et al. 2006, Robèrt 2000]. Moreover, as it is very difficult to agree on the exact damage thresholds or critical concentrations, the System Conditions provide a basis for general agreement [Upham 2000].

In *Paper I*, a framework is presented for analysing the sustainability of industrial symbioses (Fig. 2). According to the framework, sustainability principles form a conceptual basis of the assessment while industrial ecology tools, such as LCA, can be used to quantitatively assess the environmental performance of the symbiosis. After conducting the analysis, sustainability principles can be applied again in order to determine how the system should be developed to make it more sustainable. Robèrt et al. [2002] suggest that in the short term, some violation(s) of the System Conditions (‘intermediate solution(s)’) can be accepted provided that these are likely to help the system to reach a more sustainable path in the longer term (‘permanent solution(s)’). A good example here could be the gradual substitution of fossil fuels with other energy carriers (for more discussion on the matter, please refer to *Paper I*). The sustainability principles were not applied further in *Papers II–IV* but they are studied in the Results section. They are also applied in Pakarinen et al. [2010] to assess the evolution of the case study symbiosis of this study.

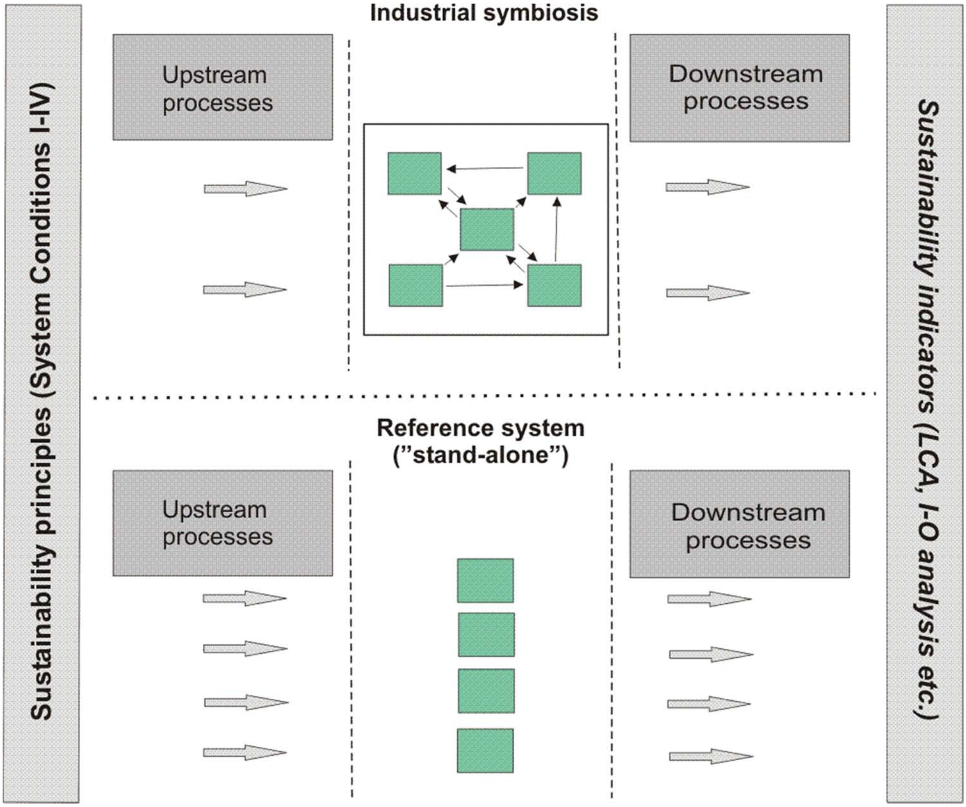

Figure 2. The sustainability principles (System Conditions I–IV) can guide the assessment of the sustainability of the case study symbiosis. Sustainability indicators, based on the use of different industrial ecology tools, such as LCA, are applied for quantification of the actual environmental performance (*Paper I*).

3.3 Assessing the environmental performance of the IS Case

The analysis was conducted with life cycle assessment (LCA) based on the ISO 14000 series [ISO 2006a, ISO 2006b]. LCA is a method for assessing the potential environmental impacts and resources used during the entire life cycle of a product or service, from raw material extraction through production and use to waste management. LCA consists of four phases [ISO 2006a]: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. The goal and scope definition phase includes a definition of the aims, intended application and system boundaries of the study. The functional unit of the study is also defined in this phase. The functional unit describes the function of the product or process under study [Finnveden et al. 2009]. During the life cycle inventory phase, data on all the inputs and outputs related to the product over its life cycle are compiled. Life cycle impact assessment consists of five components, some of which are mandatory and some voluntary [ISO 2006b]. In classification, inventory data are assigned to certain impact categories, such as climate change, acidification, eutrophication, etc. In characterisation, impact category indicators are calculated applying characterisation factors. Classification and characterisation are mandatory while the last three components, normalisation, grouping and weighing, are optional. In normalisation, impact category indicator results are calculated in relation to certain reference value(s).

In this study, the IS Case was treated as a ‘black box’, i.e., one of the life cycle phases of the product system (Fig. 3). The other life cycle phases were the production of raw materials (including transportation) used by the IS Case, the production of energy and fuels (including transportation) used by the IS Case, and the disposal and recovery of waste materials. All these three phases took place outside the IS. System expansion was used for the recycled waste materials. This means that the inputs and outputs avoided by recycling waste were deducted from the total. The functional unit of the study was the annual production of the IS Case (in tonnes or GWh during 2005) at the gate of the park. Thus, all the production and consumption figures of the system refer to 2005 unless otherwise stated. As the products of the symbiosis were mainly intermediate products for other industries, the environmental impacts were analysed from cradle to gate, i.e., the downstream impacts were not taken into account.

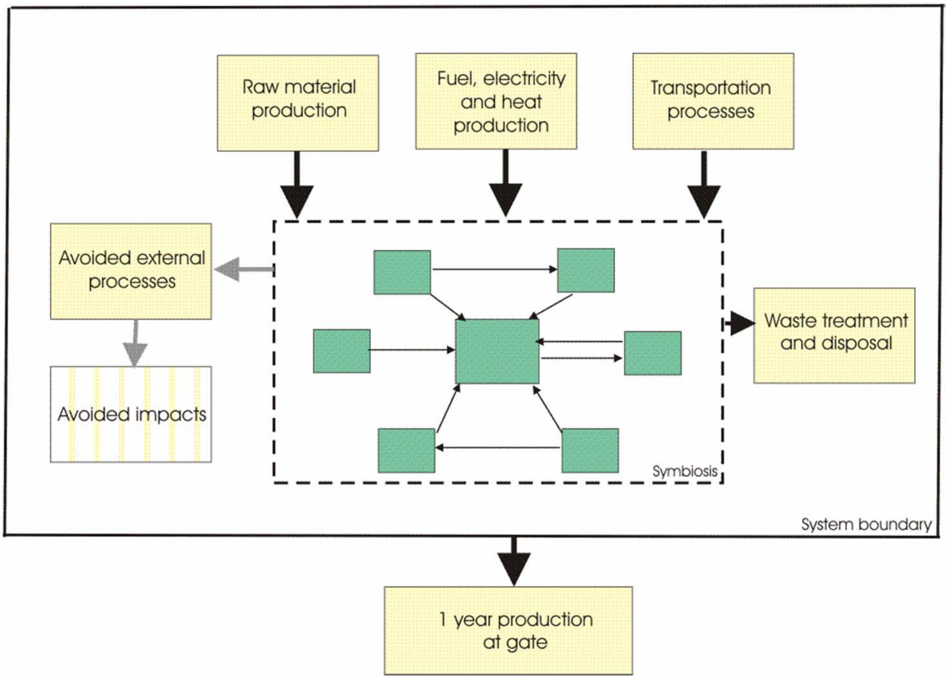

Figure 3. Processes included in the study. The IS Case was treated as a "'black-box', i.e., as one of the life cycle phases of the system. The other life cycle phases included the production of raw materials; production of fuels, electricity and heat; transportation processes; waste treatment and disposal; and external processes that were avoided through waste recycling or recovery. The outer line represents the system boundary of the study and the inner dashed line marks the boundary of the symbiosis. The functional unit of the study is one year's production (in tonnes or GWh during 2005) of the whole symbiosis at the gate of the park.

The data on the direct raw material and energy use and on emissions and waste production were retrieved from the IS Case companies themselves, from their environmental permits and from the VAHTI database of the Finnish Environmental Administration[2]. Data on the production of raw materials and fuels and the recycling and treatment of waste stemmed from the available LCA databases [mainly the Ecoinvent database[3], Swiss Center for Life Cycle Inventories 2007], the VAHTI database [Finnish Environment Administration 2009], companies' environmental reports and literature (see *Papers II* and *III* for a more thorough

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[2] The VAHTI database is an emissions control and monitoring database of the Finnish Environmental Administration.

[3] Ecoinvent: www.ecoinvent.ch.

description of the data sources used). The calculations were conducted using the KCL-ECO LCA software [Anon. 2004].

The life cycle inventory (LCI) analysis was conducted with the KCL-ECO 4.0 program. KCL-ECO is a commercially available LCA software program. It was first developed by the Oy Keskuslaboratorio Ab (KCL) research company, which is a limited company owned by the Finnish pulp, paper and board industries. Presently, the program is owned and developed by the VTT Technical Research Centre of Finland. Despite being developed specifically for pulp and paper industries, the program is suitable for analysing all kinds of systems. It has a graphical interface and includes both LCI and life cycle impact assessment (LCIA) phases. In this study, KCL-ECO was only used for the LCI analysis. The results of the LCI analysis were fed into Excel with which the LCIA was conducted.

The life cycle impact assessment (LCIA) was conducted according to the ISO 14040 and 14044 standards on life cycle assessment. Characterisation factors that are generic in terms of site and time are often used for practical reasons and uncertainties about the location or time when/where the emissions are occurring [Krewitt et al. 2001, Pennington et al. 2004]. Nevertheless, many studies have shown that within some impact categories, the estimated damage between countries may vary considerably due to, for example, local environmental conditions [Krewitt et al. 2001, Seppälä et al. 2006]. As most of the processes in this study took place in Finland or Russia, Finnish-specific characterisation factors were used for impacts on acidification, eutrophication, tropospheric ozone formation and particulate matter (See Table 1 in *Paper III*). The toxicity impacts were calculated with the ReCiPe methodology [Sleeswijk et al. 2008]. Impacts on biodiversity were not taken into account.

In normalisation, the global system is often chosen for a reference situation because product life cycles can extend all over the world [Sleeswijk et al. 2008]. However, policy-makers are typically interested in results on a lower geographic scale because such results can be more directly connected with political aims. In this study, the results were normalised with European reference values, i.e. total European emissions in 2000[4] [Sleeswijk et al. 2008]. Weighing was not conducted, as weighing is usually not recommended in comparative studies presented to the public due to its subjectivity [Pennington et al. 2004].

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[4] EU_{25} supplemented with Iceland, Norway and Switzerland.

3.4 Using hybrid LCA to assess the impact of cut-off

A process-based LCA, such as the one conducted in *Papers II* and *III* and described in the beginning of Section 3.3, is based on unit processes and is specific and detailed. It necessarily results in cut-offs, however, when certain processes are left outside the boundary of the study. This is a common situation with LCA, as there seldom are enough resources to follow each flow to its cradle. In addition, the cut-off is usually based on material or economic relevance, as the environmental relevance is difficult to assess without gathering LCA data. It has been estimated that the extent of environmental impacts neglected with cut-off is in the order of 20% [Suh et al. 2004]. In *Papers II* and *III*, some of the flows were not followed all the way to extraction from the nature stage. This cut-off mainly consisted of chemicals (reported only as trade names) and raw materials used in the avoided product chains (see *Paper IV*).

In order to overcome the truncation error of process-based LCA, input-output analysis has been integrated with life cycle assessment [e.g., Suh & Huppes 2002]. In input-output life cycle assessment, an environmentally extended input-output table is used to construct an input-output life cycle assessment (IO-LCA) without using any process-based life cycle inventory data [Suh & Huppes 2005]. LCA based on input-output analysis (I-O-LCA) is more complete than process LCA but it suffers from limited process specificity. In a so-called hybrid analysis, process-based LCA and data from an environmentally extended input-output analysis are combined [Suh & Huppes 2005, Jeswani et al. 2010]. In *Paper IV*, a hybrid LCA of this kind was conducted. For this analysis the cut-off flows were converted from mass to monetary flows by multiplying them with the basic producer prices. These were obtained by combining data from a physical input-output table for 2002 [Statistics Finland 2010a], the corresponding monetary input output table, and the sectoral price indexes between 2002 and 2005 [Statistics Finland 2010b]. These flows were weighted with the corresponding emission multipliers, which were taken from an environmentally extended input-output table for Finland [Seppälä et al. 2009]. The model included monetary flows and emissions for the years 2002 and 2005 as well as the physical input-output table (PIOT) for the year 2002. A more detailed description of the approach can be found in *Paper IV* and in Seppälä et al. [2009].

For the analysis, the cut-off was divided into three components: upstream, substitution and services. As already mentioned, the upstream cut-off primarily included chemicals, lubricant oils and wood-based raw materials. The substitution cut-off consisted of cut-off flows from the product systems, which were assumed to be substituted by the by-products of the park (termed ‘avoided external processes’). These flows were mainly cardboard, oils and steel. The services included all the inputs that were not quantified in the process LCA but that were estimated based on the industry-average input coefficients of the IO-LCA (i.e., repair services and machinery maintenance). It should be pointed out that the category services also included some flows which were not services, such as machinery, spare parts and building materials. Most of the economic flows in this category were services however.

3.5 Comparisons to counterfactual stand-alone systems

The environmental impacts of the IS Case were analysed with counterfactual analysis [Salmi 2007]. In such an analysis, the effects of hypothetical changes in a system’s history on its current situation are estimated [Young et al. 2006]. Thus, counterfactuals can be defined as thought experiments used to study how a sequence of events would have unfolded if some specific element in the actual sequence had not occurred or had taken a different form. In environmental sciences counterfactual analysis has been used, for example, to study the carbon leakage from unilateral environmental tax reforms in Europe [Barker et al. 2007]. In the present study, the environmental impacts of the IS Case were compared to four different counterfactual reference systems in which the actors would be working on their own, i.e., in stand-alone mode, in order to assess the actual environmental benefits achieved through an industrial symbiosis. The reference scenarios were based on the assumption that they could represent possible alternative states of the IS Case. It must be emphasised, however, that these systems are hypothetical and do not represent any probable development of the case study symbiosis in the future. Here, the systems are termed Reference Scenarios I–IV with I representing Case 1 in *Paper II*, II represents Case 2 in *Paper II*, III refers to Reference System I in *Paper III* and IV Reference System II in *Paper III*. The main differences between the different scenarios were related to energy production.

In Reference Scenarios I and II, the GHG emissions of the IS Case system were compared to two counterfactual stand-alone systems in which the actors of the system would be working on their own (*Paper II*). In Reference Scenario I, the following assumptions were made:

- It is assumed that the power plant does not receive any wood from the pulp and paper mill, but instead increases its peat consumption and buys wood residues from the markets. It produces heat and electricity for the markets and negative emissions are thus calculated for that production. Data on the power plant's heat and electricity production were taken from the E.ON Finland Oyj's Joensuu plant, a similar-sized CHP plant that mainly uses peat and wood residues, and a small amount of landfill gas and heavy fuel oil in its energy production. The wood residues of the pulp and paper mill are assumed to be used for landscaping, thereby replacing other wood chips.
- The pulp and paper mill does not receive electricity or heat from the power plant but purchases them from the markets.
- The chlorine dioxide (ClO_2) plant and the calcium carbonate ($CaCO_3$) plant, which presently obtain electricity and steam from the pulp and paper mill, purchase energy from the markets.
- In addition, the calcium carbonate plant does not obtain flue gas from the pulp and paper mill but buys liquid CO_2 instead.

The allocation for heat and electricity was conducted according to the benefit allocation method[5]. It was assumed that the heat and electricity production of the power plant would replace the average Finnish electricity and heat production (for data sources see *Paper II*).

Reference Scenario II is the same as Reference Scenario I but the power plant uses solely peat in its energy production (see *Paper II*). As in Reference Scenario I, the allocation for heat and electricity was conducted according to the benefit allocation method.

In Reference Scenarios III and IV, the total environmental impacts of the system were included in the assessment, not only the GHG emissions. In Reference Scenario III, the following assumptions were made:

- The power plant would only produce heat and electricity for the pulp and paper mill. The local town uses electricity produced with hydropower as before but purchases the rest of its electricity demand from regular markets (representing average Finnish production). The

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[5] In the benefit allocation method, the emissions of combined heat and power (CHP) production are allocated in relation to the alternative fuel consumption ratios (see, e.g., Heljo & Laine [2005]).

town uses the average heat from the Kymenlaakso region [Finnish Energy Industries 2006].

- The calcium carbonate ($CaCO_3$) plant and the chlorine dioxide (ClO_2) plant, which currently obtain electricity and steam from the pulp and paper mill, also use average heat from Kymenlaakso and average Finnish electricity.
- It is assumed that the pulp and paper mill does not obtain any sewage sludge from the municipal wastewater treatment plant. The sewage sludge addition replaces urea and phosphorous acid in the wastewater treatment process of the pulp and paper mill. Thus, extra nitrogen and phosphorus need to be added to the system. The amount of nutrients needed was calculated with data from Valtonen [2005]. The sewage sludge is assumed to be composted instead, and negative emissions were calculated for the peat that it was assumed to replace at a ratio of 1:1.
- The calcium carbonate plant buys liquid CO_2 from the markets instead of using CO_2 from the pulp and paper mill.

Reference Scenario IV is the same as Reference Scenario III but heat is assumed to be produced with peat instead of the average heat from Kymenlaakso. Data on heat produced with peat were taken from Myllymaa et al. [2008]. Mining of the peat was also taken into account.

3.6 Potential ways to improve the IS Case

A further scenario, Reference Scenario V (representing Reference System III in *Paper III*), was constructed to further analyse the waste and emission flows of the IS Case in order to spot possibilities for additional links between the actors or for links to new actors. The potential environmental benefits of these connections were assessed. These possible new features of the symbiosis included the use of hydrogen gas from the chlorine dioxide plant in a new hydrogen plant in the IS Case[6], the use of fly ash from the power plant in forest fertilisation and treatment of municipal wastewaters from the municipality of Kouvola at the pulp and paper mill. It was assumed that the fly ash and municipal wastewater would

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[6] Presently, the hydrogen is released into the air. However, the same plant has built a hydrogen-utilising energy unit in its other chlor-alkali plant (see *Paper III*).

both reduce the need for externally produced phosphorus. In addition, the potential to use the waste heat from the pulp and paper mill in greenhouses was assessed. Assumptions concerning the aforementioned are presented in more detail in *Paper III*.

4. Results

4.1 Flows of energy and GHG emissions of the IS Case

The IS Case uses primarily wood and natural gas in its energy production (Fig. 4). In addition to the flows depicted in Figure 4, the pulp and paper mill received over 1,500 GWh of its energy consumption from black liquor originating from pulp production. The pulp and paper plant uses approximately 917,000 tonnes of wood for pulp and paper production. Part of this wood raw material is used for energy generation: pulping produces black liquor, the use of which is not included in the figures. In addition, it used 43 GWh of odorous gases from pulp production for energy generation. All in all, the IS Case purchased 326 GWh of electricity and 13 GWh of heat from outside the park in 2005. The amount of heat released in wastewater was 2,500 GWh. More detailed results are presented in the tables and figures of *Paper II.*

The GHG emissions of the IS Case (including emissions from upstream processes and transportation) totalled 653,000 tonnes of CO_2 eqv. in 2005. The direct emissions of the actors of the IS Case were 30% of the total emissions: 196,000 tonnes CO_2 eqv. (Fig. 5). The rest of the emissions were caused by the upstream processes. The contribution of the waste management processes was negligible.

Approximately 40% of the direct GHG emissions were generated by the power plant (Fig. 6). However, due to its low requirement for fossil fuels and auxiliary production inputs, its contribution to the indirect emissions was only 3% and to the total emissions 14%. The pulp and paper mill produced approximately 50% of the direct emissions and 70% of the indirect GHG emissions.

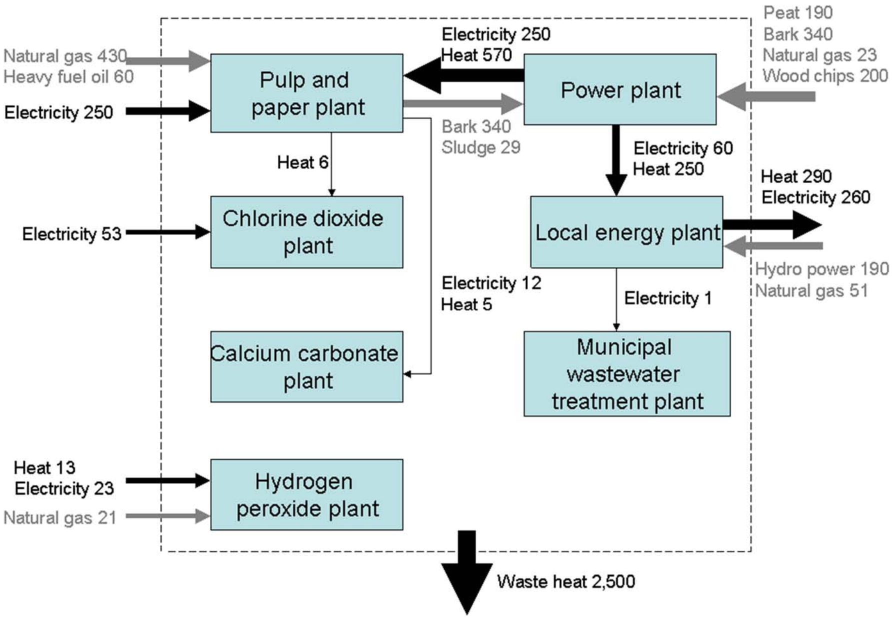

Figure 4. Direct inputs and outputs (GWh) of fuel and electricity and heat to and from the IS Case in 2005 (*Paper II*). The grey lines represent fuel flows and the black lines depict heat and electricity flows. The thickness of the arrow reflects the magnitude of the flow. In addition to the flows depicted in the figure, the pulp and paper plant uses approximately 917,000 tonnes of wood for pulp and paper production. Part of this wood raw material is used for energy generation: pulping produces black liquor, the use of which is not included in the figures.

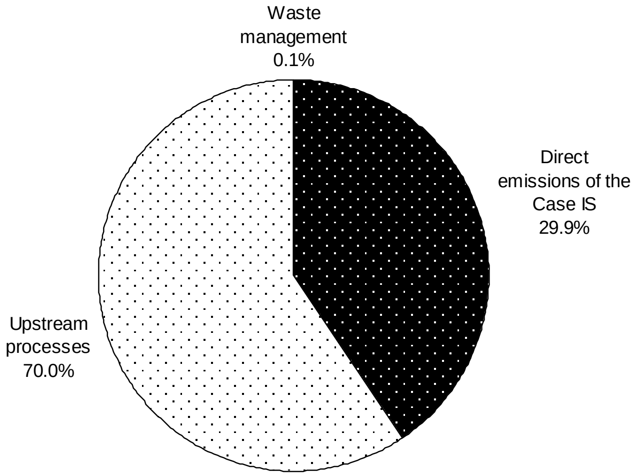

Figure 5. Contribution of direct emissions of the IS Case, emissions from upstream processes and waste management to the total GHG emissions of the IS Case (% in 2005) (*Paper II*). Most of the emissions result from upstream processes.

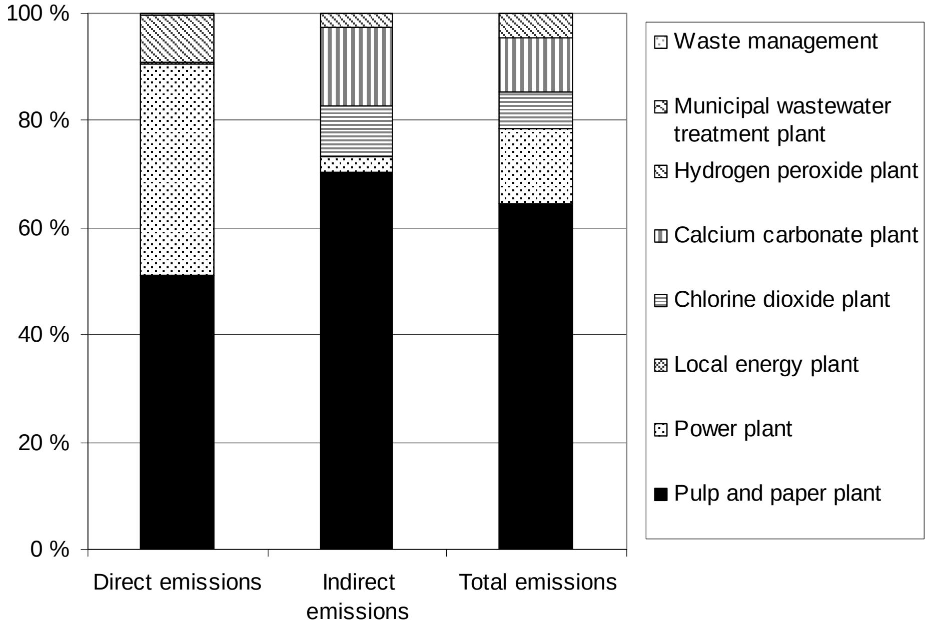

Figure 6. The contribution (%) of different actors to the direct, indirect and total GHG emissions of the IS Case in 2005. The pulp and paper plant caused most of the direct and indirect emissions. Approximately 40% of the direct emissions originated from the power plant. As it required few fossil fuels and minimal auxiliary production inputs, however, its contribution to the indirect emissions was only 3% (*Paper II*).

Of the total GHG emissions of the system, the direct emissions of the pulp and paper mill constituted approximately 15% and those of the power plant 12% (Fig. 7). The other main emission sources were calcium oxide (CaO) production used by the calcium carbonate plant, externally produced electricity for the pulp and paper mill, calcite, natural gas and sodium hydroxide production. All of the aforementioned were consumed mainly by the pulp and paper mill, except for calcium oxide, which was used by the calcium carbonate plant. Altogether, the production of pigments, fillers and other chemicals used by the pulp and paper mill caused over 35% of the total GHG emissions of the system. Since many of the pigments and fillers are transported over fairly long distances, transportation makes up approximately 11% of the total GHG emissions related to the production of the pigments. The role of forestry was very small. It should be noted that in this study, only fossil carbon was considered. If biogenic carbon had also been taken into account, the forestry processes would probably have made a larger contribution to the results.

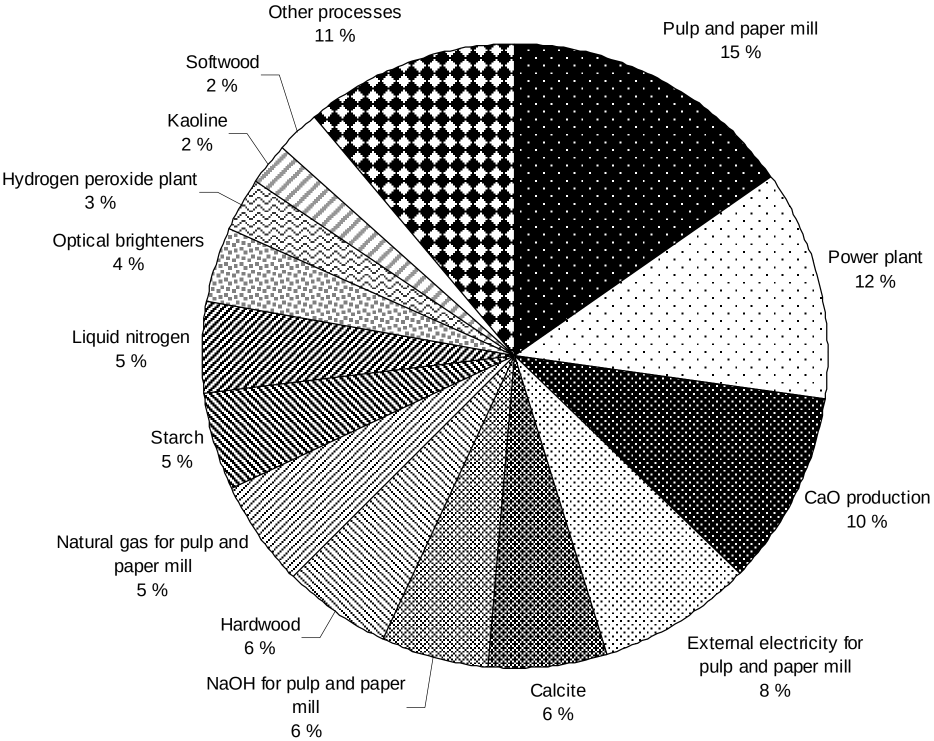

Figure 7. Main processes contributing to the total GHG emissions of the IS Case system in 2005 (*Paper II*). The largest contributors were the direct emissions of the pulp and paper plant, and the power plant, and the production of CaO and external electricity. Altogether the system included almost 70 processes.

4.2 Total environmental impacts of the IS Case

Based on the normalised values, the acidification impacts were the highest, followed by terrestrial eutrophication, tropospheric ozone formation (human health impacts), climate change and impacts on particulate matter formation (Fig. 8, see also Appendix A of this publication and Appendix 1 of *Paper III* for the detailed inventory results). The normalised values for climate change, particulate matter formation and aquatic eutrophication were only 20–40% of those for acidification. Most of the acidification, terrestrial eutrophication and tropospheric ozone formation originated from emissions of nitrogen oxides. The impacts on toxicity were between $1.21*10^{-6}$ and $8.05*10^{-6}$ for the toxicity impact categories and $1.95*10^{6}$ for abiotic resource depletion. They were thus very small compared with the other impact categories and were omitted from further analysis.

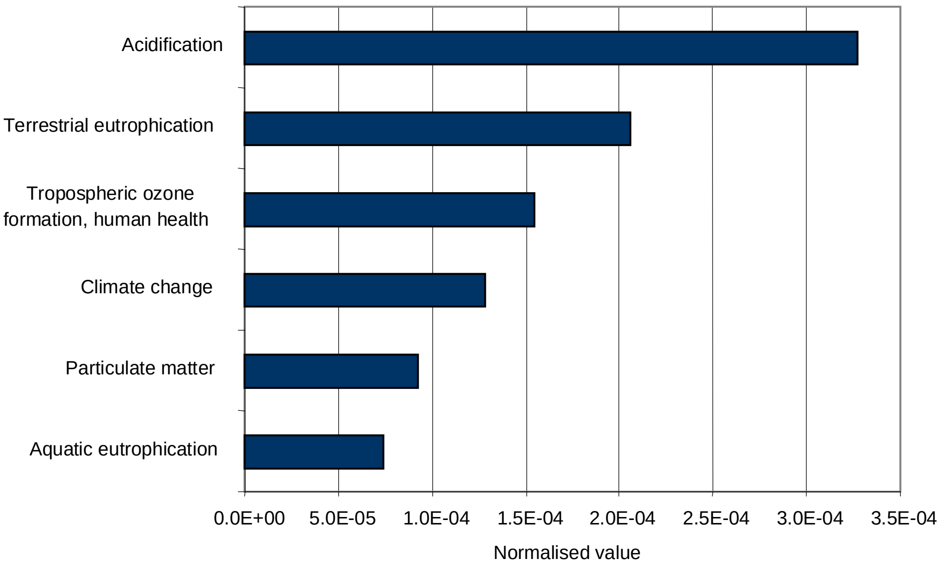

Figure 8. Normalised values for different impact categories in the IS Case. Based on the normalised values, the acidification impacts were the highest, followed by terrestrial eutrophication, the human health effects of tropospheric ozone formation and climate change impacts.

Of the different life cycle stages (upstream processes [divided into raw material extraction and processing, and energy and fuel production and extraction], production within the symbiosis, waste management processes and impacts avoided through recovered materials), raw material production and processing made the largest overall contribution to the results in most impact categories (Fig. 9). Fuel production and energy generation contributed approximately 19% to the climate change impacts. Its share in the other impact categories was between 3 and 15%. The shares of waste management and avoided emissions through waste recovery were very small, less than 1% and 1.5% in all the impact categories for waste management and avoided impacts, respectively.

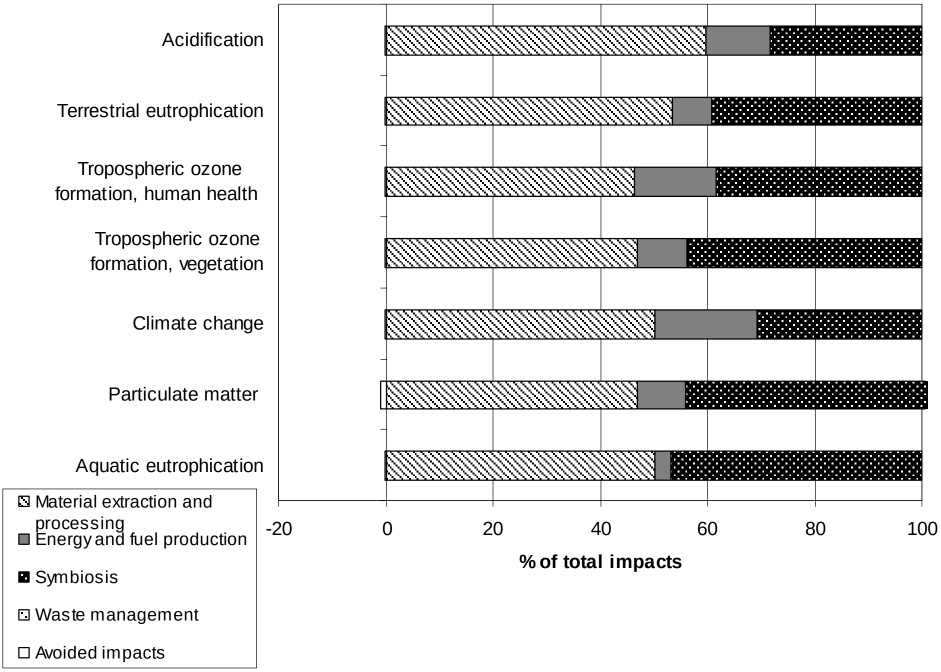

Figure 9. Normalised values presented according to different life cycle phases of the IS Case ('Symbiosis' stands for inputs and outputs to/from the symbiosis). In all the impact categories, extraction and processing of raw materials along with energy and fuel production formed over 50% of the total impacts. Normalised values for freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity and abiotic resource depletion were so small that they were omitted from the figure. The contributions of waste management processes and avoided impacts are so small that they are not visible in the figure except for the small contribution of avoided impacts in particulate matter formation (*Paper III*).

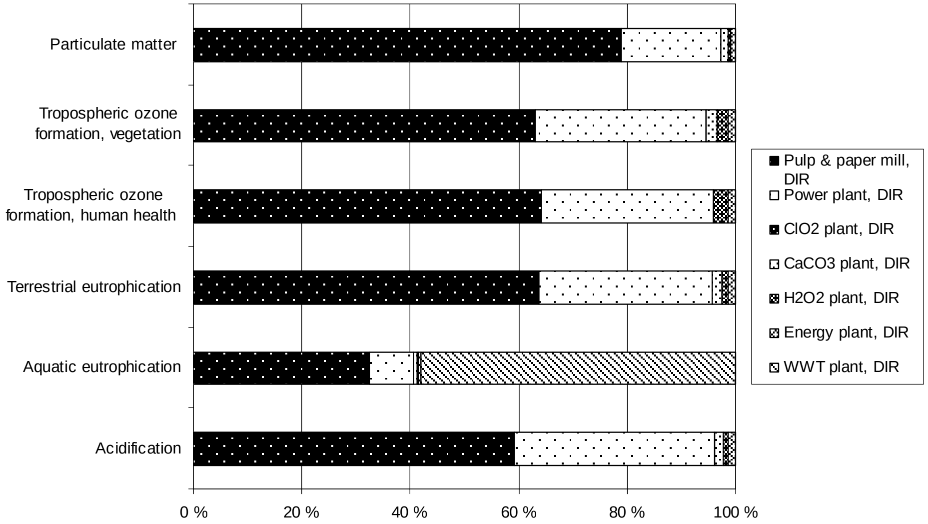

Figure 10a. Contribution of the different actors of the IS Case to the direct impacts of the IS Case. WWT stands for the municipal wastewater treatment plant.

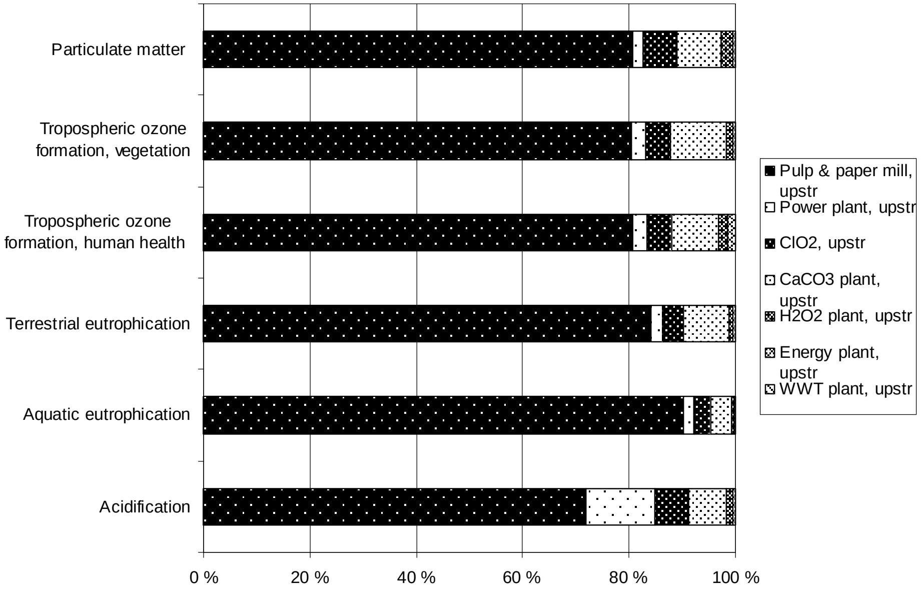

Figure 10b. Contribution of the different actors of the IS Case to the total upstream impacts. WWT stands for the municipal wastewater treatment plant.

As could be expected, due to the large size of the pulp and paper mill, over 60% of all impacts, except for terrestrial ecotoxicity, were caused by the mill itself and its related upstream processes. The contribution of the mill to the particulate matter, acidification and tropospheric ozone formation impacts was over 70%. Its direct emissions caused over 50% of the total impacts originating from the symbiosis in all other impact categories except the toxic impacts and aquatic eutrophication (Fig. 10a). The municipal wastewater treatment plant was responsible for over 50% of the aquatic eutrophication impacts of the symbiosis. The power plant contributed approximately 30% of all impacts studied in Figure 10a except for particulate matter formation and aquatic eutrophication. The contribution of the other actors was minor.

In the impacts of the upstream processes, processes related to the pulp and paper mill were responsible for most impacts in all the impact categories (Fig. 10b). The role of the power plant was small in all other impact categories except for acidification impacts. The contribution of the calcium carbonate plant ranged from 4% to 10% and that of the chlorine dioxide plant from 3% to 6%. The role of the other actors was small.

4.3 Extending the upstream system boundary with hybrid LCA

The important role of the upstream processes in the total impacts can be seen from the results of *Papers II* and *III* presented in Sections 4.1 and 4.2. As mentioned in Sections 4.1 and 4.2, the total impacts caused by the direct emissions of the symbiosis amounted to less than half of all the impacts. The more complete inventory using the hybrid LCA methods further supported this conclusion (*Paper IV*). As results from the hybrid LCA show, the process-based LCA covered approximately 80–90% of the total impacts in most impact categories, except for the metal depletion and terrestrial ecotoxicity impacts (Table 1). Most of the cut-off (impacts not captured by the process LCA) consisted of services. The share of direct emissions was particularly small in freshwater ecotoxicity, metal depletion and land use impact categories. Thus, if the analysis had only been based on direct emissions, the size and relative importance of the different environmental impacts would have been identified erroneously.

Table 1. Direct emissions, impacts calculated with process-based LCA and hybrid LCA compared (adapted from *Paper IV*). 'Direct' refers to the direct emissions and resource use of the symbiosis actors. For an explanation of process LCA and hybrid LCA, see Section 3.3. The table shows that the direct emissions and resource use of the symbiosis only represent a minor fraction of the total impacts. The process-based LCA covered over 80% of the total impacts in most impact categories.

			Cut-off			
	DIRECT	Process-LCA	Up-stream	Substi-tution	Ser-vices	Hybrid-LCA
Climate change	26%	88%	6%	-2%	8%	100%
Terrestrial acidification	24%	87%	5%	-1%	9%	100%
Fresh water eutrophication	55%	91%	3%	0%	6%	100%
Marine eutrophication	38%	84%	7%	0%	10%	100%
Photochemical oxidants	36%	89%	4%	-1%	8%	100%
Freshwater ecotoxicity	7%	78%	5%	-1%	18%	100%
Marine ecotoxicity	25%	78%	6%	-3%	19%	100%
Terrestrial ecotoxicity	27%	62%	10%	-3%	31%	100%
Human toxicity	54%	89%	3%	-1%	9%	100%
Particulate matter	38%	88%	3%	-1%	10%	100%
Metal depletion	1%	19%	9%	-22%	94%	100%
Fossil depletion	21%	83%	9%	-1%	9%	100%
Land use	0%	97%	2%	0%	1%	100%

4.4 Impacts of the reference scenarios

The environmental impacts of the IS Case were compared with those of four counterfactual reference scenarios in which the actors of the systems would be operating in isolation, i.e., not in symbiosis. In Reference Scenarios I and II, only the GHG emissions were studied (Fig. 11). The main difference between these two scenarios was that in Reference Scenario I, the power plant was replaced with a CHP plant that used both peat and wood in energy production. In Reference Scenario II it was replaced with a CHP plant that used only peat as a fuel. For a more detailed description of the differences between the scenarios, see Section 3.5. Both scenarios resulted in increased emissions. In Reference Scenario I, emissions would grow by 40% and in Reference Scenario II by 75%. Emissions from the pulp and paper mill increased because it no longer received electricity and heat from the power plant but purchased them from the markets. Emissions from the power plant grew, particularly in Reference Scenario II, because in that scenario it only used peat as a fuel.

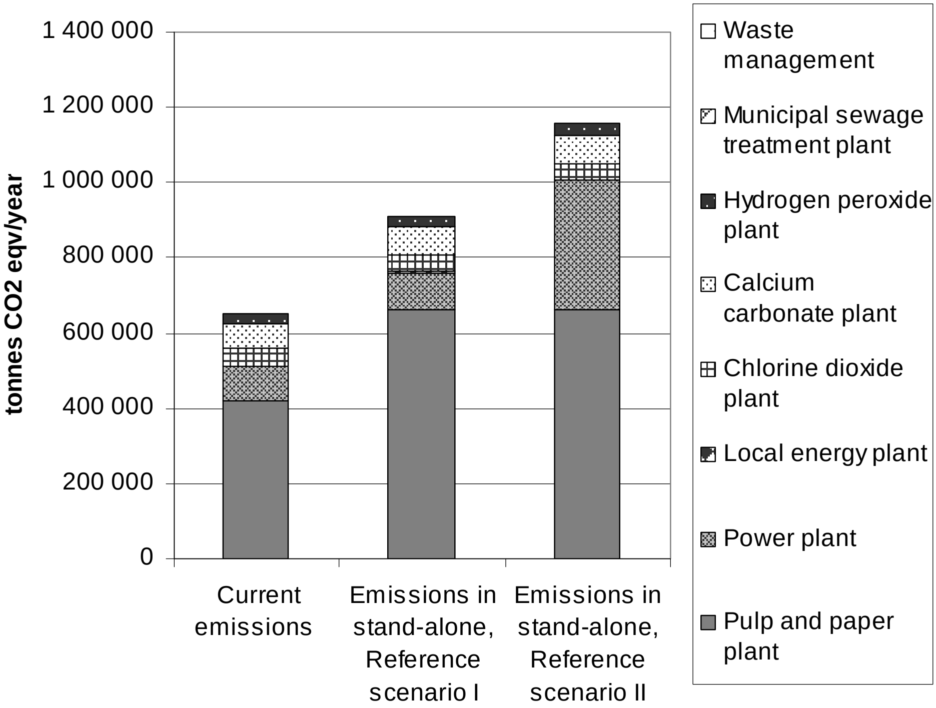

Figure 11. Current emissions compared with a situation in which actors operate on their own. Reference Scenario I: the power plant is replaced by a CHP plant that uses both peat and wood (approximately 45–55% ratio). Reference Scenario II: the power plant is replaced by a CHP plant that uses only peat (*Paper II*).

In Reference Scenarios III and IV, the total environmental impacts were studied. In Reference Scenario III, the power plant would only produce heat and electricity for the pulp and paper mill. The local town purchases electricity from regular markets (representing average Finnish production) and uses average heat from the Kymenlaakso region [Finnish Energy Industries 2006]. It is also assumed that the pulp and paper mill does not obtain any sewage sludge from the municipal wastewater treatment plant and therefore needs more nitrogen and phosphorus. In addition, the calcium carbonate plant buys liquid CO_2 from the markets instead of using CO_2 from the pulp and paper mill. Reference Scenario IV is the same as Reference Scenario III, but heat is assumed to be produced with peat instead of using the average heat from Kymenlaakso. For more details on the scenarios, see Section 3.5.

As shown in Figure 12, in most of the impact categories, the reference scenarios had higher impacts than the IS Case. In Reference Scenario III, the impacts on climate change increase by 12% and on acidification and particulate matter formation by approximately 5%. In Reference Scenario IV, the changes would be larger in all the impact categories, particularly acidification, which would grow by nearly 40%. In other impact categories, except for aquatic eutrophication, the increase would be 10–20%.

The assumed increases in the recycling of by-products generated by the IS Case (Reference Scenario V, potential improvements, see Section 3.6) would result in a decrease of almost 30% in aquatic eutrophication impacts (Fig. 12). The other impacts would decrease by less than 10%.

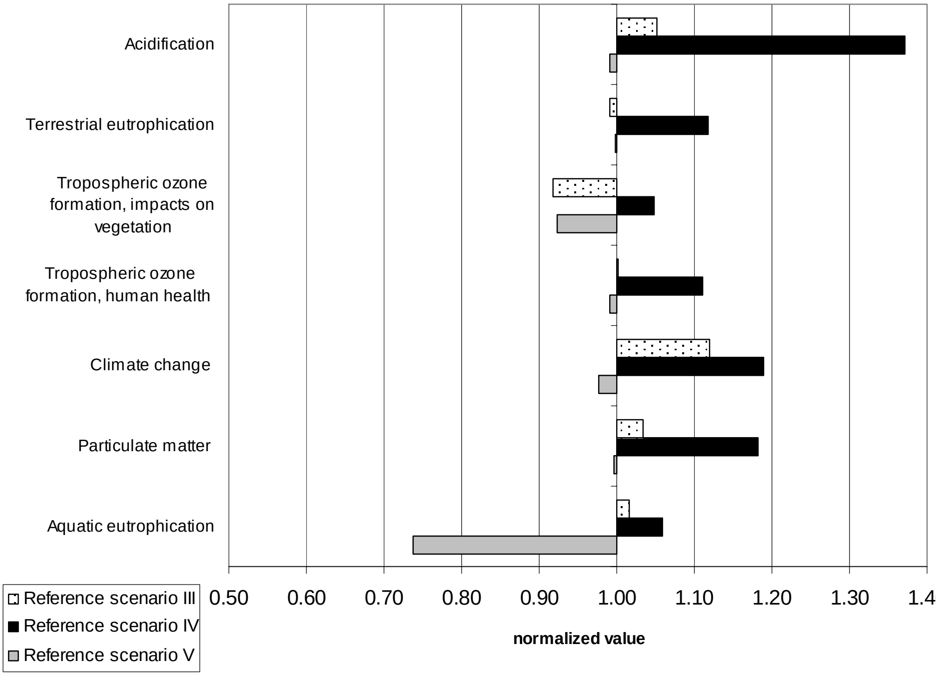

Figure 12. Environmental impacts of Reference Scenarios III, IV and V in relation to those of the IS Case (the environmental impacts of the IS Case yield a value of 1). The normalised values for freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity and abiotic resource depletion were so small that they were omitted from the Figure (*Paper III*).

The main processes contributing to aquatic eutrophication, particulate matter formation, acidification and terrestrial eutrophication were then studied in more detail (see *Paper III* and Fig. 13). Over the whole life cycle of the production system, the largest contributors to these impacts (except for aquatic eutrophication) in the IS Case and Reference Scenarios III–V were the pulp and paper mill, the power plant, the production of potato starch, optical brighteners and sodium hydroxide, transportation of kaolin and quicklime and the production of hardwood[7]. The largest contributors to the aquatic eutrophication impacts in the IS Case and Reference Scenarios III and IV were the municipal wastewater treatment plant (the Akanoja sewage plant in Fig. 13a) and sodium hydroxide production (consumed mainly by the pulp and paper mill). As municipal wastewaters are treated at the pulp and paper mill in Reference Scenario V, there are no emissions from the municipal wastewater treatment plant.

The fact that the environmental impacts of Reference Scenarios III and IV are higher than those of the IS Case is mainly due to differences in energy production. In Reference Scenarios III and IV, the emissions originating from the power plant, which affect especially those that affect the impacts related to the NO_X emissions, decrease compared with those of the IS Case. However, at the same time emissions from the production of district heating and electricity outside the IS Case increase, which affects, in particular, the CO_2 emissions. The further increase in CO_2 emissions is due to the fact that the pulp and paper mill no longer delivers part of its CO_2 to the calcium carbonate plant. Furthermore, in Reference Scenario IV, in which more peat is consumed, the CO_2, NO_X and SO_2 emissions from energy production are higher. The other processes were only of minor significance.

The large contribution of optical brighteners is perhaps surprising considering that the amount used was fairly small: 1,550 tonnes (of 100% purity). The production of optical brighteners is very energy-intensive compared to that of some other bleaching chemicals such as H_2O_2, but, on the other hand, the amount of chemicals needed is much lower.

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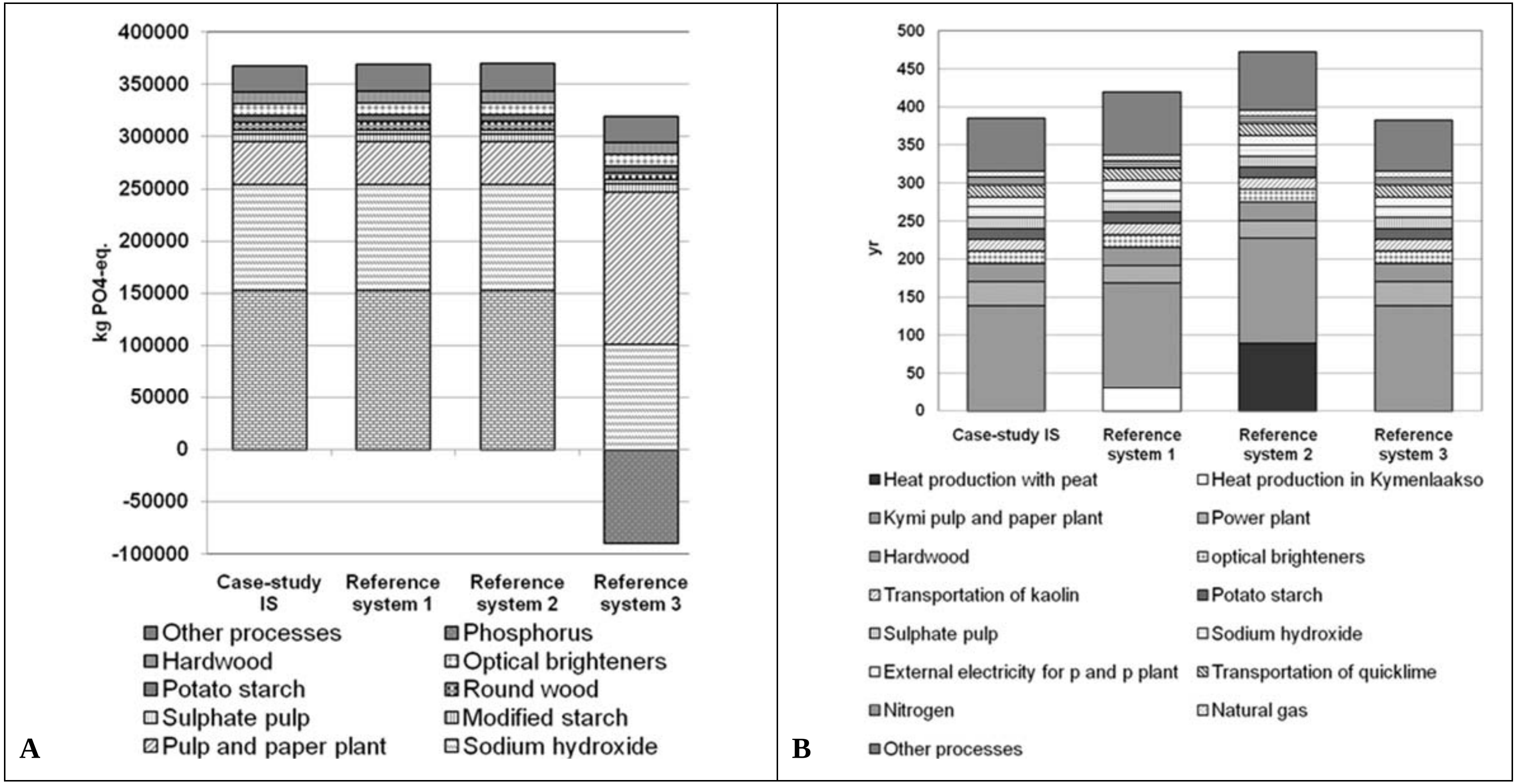
[7] All of these processes, except most of the quicklime, were consumed by the pulp and paper mill. Quicklime was mainly consumed by the calcium carbonate plant.


A
kg PO4-eq.
400000
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-100000
Case-study IS
Reference system 1
Reference system 2
Reference system 3
Other processes
Phosphorus
Hardwood
Optical brighteners
Potato starch
Round wood
Sulphate pulp
Modified starch
Pulp and paper plant
Sodium hydroxide
B
yr
500
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400
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300
250
200
150
100
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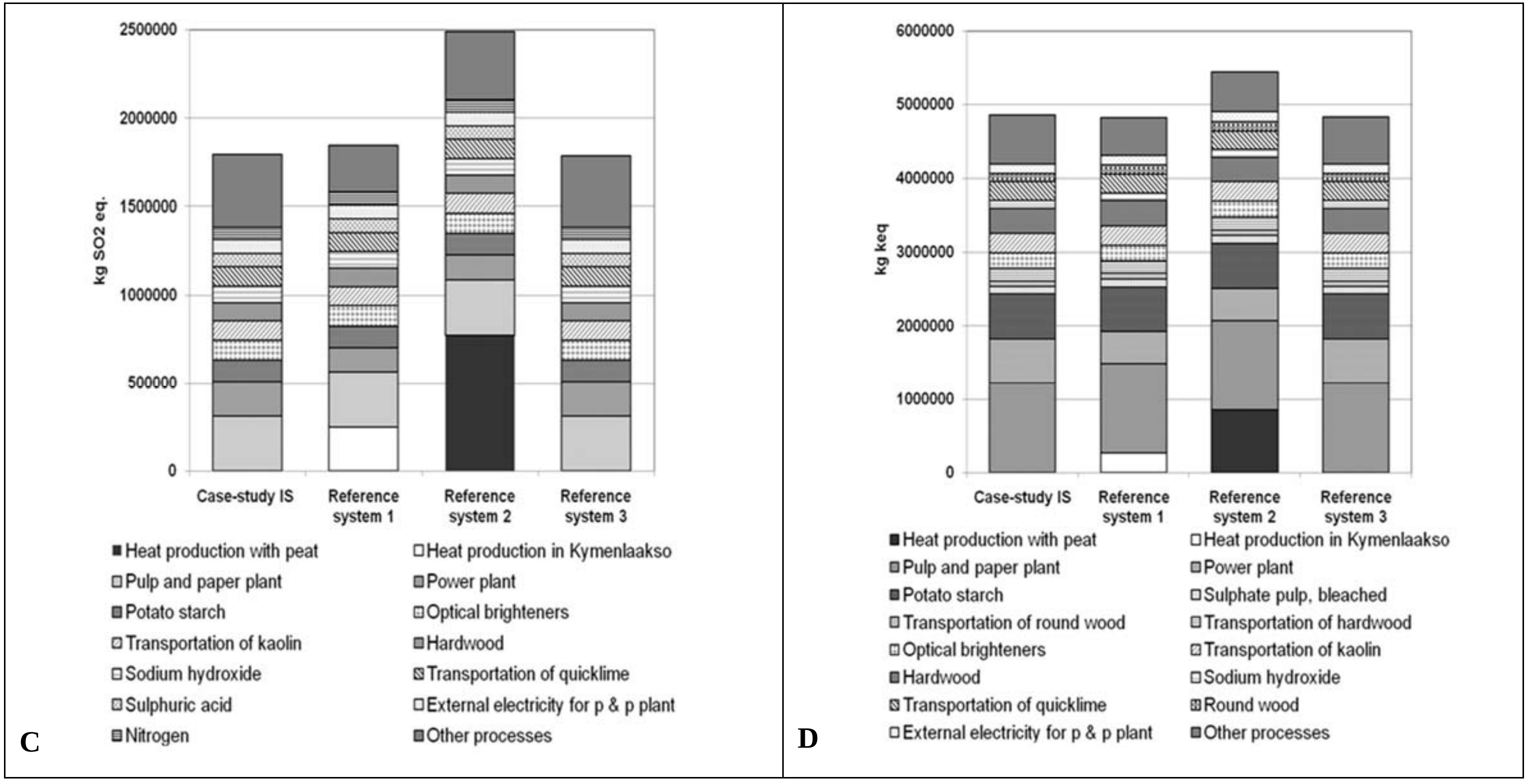
0
Case-study IS
Reference system 1
Reference system 2
Reference system 3
Heat production with peat
Heat production in Kymenlaakso
Kymi pulp and paper plant
Power plant
Hardwood
optical brighteners
Transportation of kaolin
Potato starch
Sulphate pulp
Sodium hydroxide
External electricity for p and p plant
Transportation of quicklime
Nitrogen
Natural gas
Other processes



Figures 13a–d. A comparison of the contributions of different processes in different reference scenarios and in the IS Case in terms of the most important impact categories: a) aquatic eutrophication, b) particulate matter formation, c) acidification and d) terrestrial eutrophication (*Paper III*). The fact that the environmental impacts of Reference Scenarios III and IV are higher than those of the IS Case is mainly due to changes in energy production. Reference Scenario V results in considerably lower aquatic eutrophication impacts than the other reference scenarios because municipal wastewaters are treated at the pulp and paper mill. Reference system 1 refers to Reference Scenario III. Reference system 2 to Reference Scenario IV, and Reference system 3 to Reference Scenario V.

4.5 Sensitivity analysis

The main uncertainties of this study relate to the data on upstream processes. The data on the amount of raw materials, fuels and energy used have been received directly from the actors of the IS Case. They are thus fairly accurate, but the data on the production of these materials and fuels are mainly generic and originate from different databases. They therefore do not necessarily represent the actual production processes. Consequently, the data sources of those upstream processes that had the largest effect on the results were varied in the sensitivity analysis. For more detailed results see *Paper III*. Four different scenarios for the sensitivity analysis were constructed:

- In Scenario 1, external electricity purchased by the pulp and paper mill was assumed to represent the electricity profile of the Finnish forest industries in 2007 [Finnish Forest Industries Federation 2009] instead of the average electricity used in Finland.
- In Scenario 2, the transportation distance of kaolin was changed. In the IS Case, it was assumed that 1/3 of the kaolin originated from the USA and 2/3 from the UK. The transportation method was assumed to be a roll-on ship at sea and a fully loaded Euro3 truck on land. In the sensitivity assessment, all the kaolin was assumed to be imported from the UK. The transportation method remained the same.
- In Scenario 3, the data source used for optical brightener production was different to that in the IS Case. Instead of using the Ecoinvent Database [Swiss Centre for Life Cycle Inventories 2008], data from Scheringer et al. [1999] were used.
- In Scenario 4, it was assumed that the pulp and paper mill used maize starch instead of potato starch. Data on maize starch were taken from the Ecoinvent database v. 2.01 [Swiss Center for Life Cycle Inventories 2007].

The impact of these factors was less than 10% on the main impact categories for all scenarios (see Fig. 14 and *Paper III*). Scenario 3 caused the greatest changes: acidification impacts decreased by 8% and terrestrial eutrophication impacts by 5%.

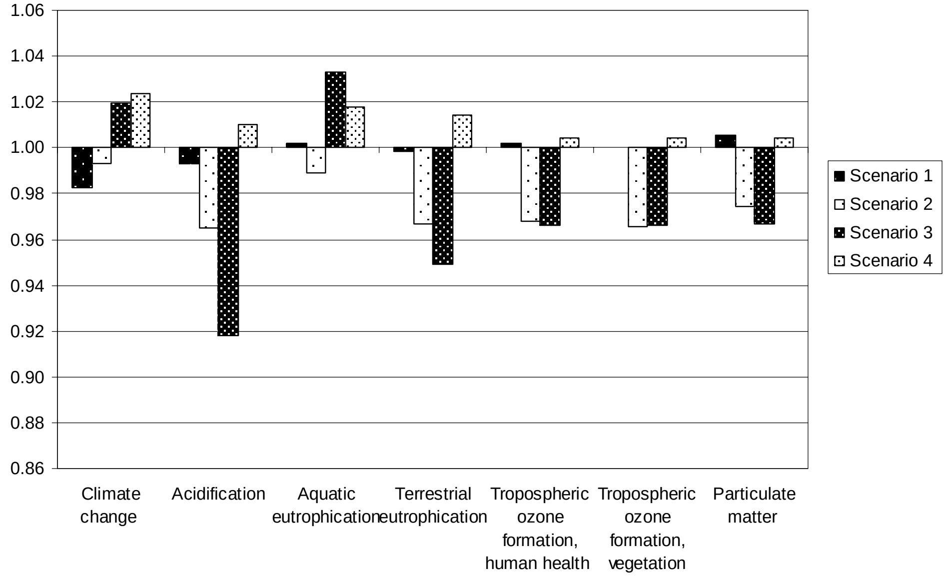


Figure 14. Sensitivity of the main impacts in the different scenarios (*Paper III*). The change in the impacts was less than 10% in the main impact categories. The greatest changes were caused by Scenario 3, which resulted in an 8% decrease in acidification impacts and a 5% increase in terrestrial eutrophication impacts.

4.6 IS system condition analysis

Section 1 introduced the Natural Step principles. *Paper I* presents a framework for assessing the sustainability of the IS Case. Based on the results presented in *Papers II–IV*, some conclusions can be drawn (Table 2). With regard to System Condition I, resource depletion was not assessed in the counterfactual analysis. The normalised life cycle impacts on the abiotic resource depletion of the IS Case were very small, however, which implies that the IS Case does contribute to reducing the throughput of minerals that are scarce in nature. Nevertheless, according to *Paper IV,* the process-based LCA only covered circa 20% of the total metal use of the system. Most of the metal use stems from purchased services. The use of fossil fuels was studied in *Paper II* (question 3 of System Condition I in Table 2). The system mainly uses renewable fuels, i.e., wood-based fuels and hydropower, in its energy production. The increase in the total greenhouse gas emissions compared to stand-alone production is mainly caused by increased fossil fuel consumption. Thus, on the basis of the results it can be argued that the IS Case does reduce the dependency on fossil fuels.

Table 2. Contribution of the case study symbiosis to the questions of the IS System Condition Analysis presented in *Paper I*. The IS Case impacts regional and global levels through supply chains. Each System Condition is analysed with the question: ‘Does the IS Case systematically contribute to…?’

System Condition I:	**Yes**	**Partly**	**No / not assessed**
A reduction in the throughput of minerals that are scarce in nature		*X*	
More eco-efficient use of extracted materials	*X*		
A reduction in the dependence on fossil fuels	*X*		
System Condition II:			
Substitution of substances that are persistent and nondegradable in nature		*X*	
More eco-efficient use of materials and products	*X*		
System Condition III:			
Phasing out destructive patterns of interference with the ecosystems		*X*	
Only extracting resources from well-managed ecosystems		*X*	
Favouring activities that consume less area			*X*
System Condition IV:			
Reducing risks to human health caused by the pollution of the environment		*X*	
Preserving resources for future generations (through systematic dematerialisation and substitution)		*X*	
Not undermining the living conditions of the world’s poor			*X*

The total material use was not calculated in this study (System Conditions II and III). In an industrial symbiosis, however, waste or side-product flows are used by the actors of the symbiosis, which implies that total material flows are reduced through the operation of the IS Case. Overall, it can be argued that many of the emissions studied in *Papers II–IV* are persistent and non-degradable in nature. The overall environmental impacts of the IS Case were lower than those of Reference Scenarios I–IV. Thus, it seems that the IS Case does contribute to the substitution or reduction of substances that are persistent and non-degradable in nature. Land use was assessed in *Paper IV* but was not compared with systems operating separately. As the system largely relies on wood as a source of pulp, paper and fuel, it is clear that its operations contribute to land use. The pulp and paper mill states that all the wood it uses, including imports, stems from a PEFC-certified chain of custody [UPM 2005]. This implies that at least in terms of its wood consumption, the system contributes to the extraction of resources only from well-managed eco-systems and to the phasing out of destructive patterns of interference with the ecosystems.

Social impacts (System Condition IV) were not considered in this study. However, some impact categories studied in *Papers III* and *IV* assessed human health impacts. Human health impacts of tropospheric ozone formation as well as particulate matter were studied in the counterfactual analysis of *Paper III*. According to the results in both impacts categories, the IS Case resulted in lower impacts than Reference Scenarios III and IV.

5. Discussion

5.1 Environmental performance of the IS Case

To date, few reported studies have assessed the overall environmental or sustainability benefits of industrial symbiosis networks. At the same time tools potential for these kinds of analyses have been developed rapidly. Most studies on industrial symbioses conducted until now concentrate on one or a limited number of factors. They have typically also used a narrow approach to the spatial system boundaries, considering only the impacts taking place within the symbiosis [Singh et al. 2007]. While it can be argued that material and energy use are central indicators of the IS Case – as the exchange of materials and energy is a core feature of industrial symbioses and very useful when identifying opportunities to enhance cooperation among firms – they are still not enough to reach conclusions about the sustainability of the system as a whole.

In this study, the overall environmental impacts of a case study industrial symbiosis were analysed using life cycle assessment. The analysis was further extended from the traditional process-based LCA to the so-called hybrid LCA, which combines input-output analysis and process-based LCA. The results of the study showed that the impacts occurring outside the symbiosis may be high. Thus, the overall results of this study support a supply-chain-based and non-regional approach for assessing the benefits of industrial symbioses because the direct emissions of the symbiosis only represent a minor fraction of its total environmental impacts.

Similar results have been reported for different kinds of systems in the literature, for example, by Lenzen et al. [2003]. In their study on the environmental impacts of the Second Sydney Airport proposal, the authors extended the environmental impact assessment (EIA) with an input-output analysis to cover the effects occurring off-site. The results showed that indirect impacts were considerable for all the factors studied. Matthews et al. [2008] present the same conclusion for carbon footprints, estimating that for the average industry, direct emissions and emissions from energy inputs only make up approximately 26% of the total life cycle emissions. Therefore, when assessing the sustainability of an eco-industrial park, the use of a more holistic approach such as LCA is supported. Singh et al. [2007] conclude in their study that LCA is a very useful tool for analysing and comparing different designs of industrial symbioses. Similarly, LCA can be applied when looking at industrial symbioses already in operation.

The results also imply that when developing or initiating an industrial symbiosis, the analysis should be extended to include off-site impacts, as these may be decisively high in relation to impacts within the symbiosis. As *Papers II–IV* show, an assessment that only considers the symbiosis would only cover a minor part of the overall environmental impacts caused by the system. Extending the analysis through the use of a hybrid LCA analysis further decreases the share of direct emissions.

When the environmental issues considered are global, such as climate change, assessments that are limited to local or even national boundaries suffer from considerable flaws [see also e.g. Hertwich & Peters 2009 on the carbon flows of international trade]. When assessing and promoting local sustainability, e.g., through symbiosis, it is important to avoid shifting problems to different locations. As Jacobsen [2006] points out, the industrial symbiosis exchanges are only one element within the comprehensive process of improving the environmental performance of a number of companies. It should therefore not be regarded as a definitive solution but as part of a process of reducing the total environmental impact of the individual company.

It can be argued that a central environmental driver for industrial symbiosis is increased material efficiency through recycling and the resulting avoidance and reduction of the upstream effects of resource extraction and primary production. Chertow [2000] points out that by using a systems approach, industrial ecology considers each step and stage of process development in order to optimise material and energy flows. In some cases it may be appropriate to reduce a waste stream while in others it may be optimal to feed it into another business. The results of this study, however, support the notion that in order to assess the environmental relevance of a particular flow, quantitative life-cycle-based methods are needed. The value of LCA lies in the possibility of identifying these flows, the reduction of which yields the greatest overall environmental benefits. For example, LCA can be applied to detect areas of improvement or to assess the environmental benefits of additional symbiotic links. As Reference Scenario V showed, the greatest additional environmental benefits could be obtained by replacing phosphorus at the pulp and paper mill with municipal sewage sludge and by saving phosphorus fertiliser by using fly ash for forest fertilisation.

In Section 4.6, the environmental impacts of the IS Case were analysed through a set of questions based on the Natural Step principles [Robèrt et al. 2002]. Not all the aspects of the Natural Step principles were assessed in the analysis but the results indicate that in many aspects, the system does operate according to the principles. The evolution of the IS Case has been analysed with the TNS framework by Pakarinen et al. [2010]. In the study it was found that during the 115 years studied, the system moved towards greater sustainability in many aspects. In order to address all the aspects of the Natural Step principles, other methods would be needed in addition to LCA. Life cycle assessment has been complemented with life cycle costing (LCC) [e.g., Gluch & Baumann 2004]. Social aspects have been included in the social life cycle assessment [Griesshammer et al. 2006]. Deepening and broadening of the scope of LCA has been discussed further by, e.g., Jeswani et al. [2010].

All in all, the Natural Step principles pose an interesting framework for assessing the sustainability of industrial symbioses and other kinds of industrial systems. The value of the principles lies in the fact that they can introduce a strategic aspect into environmental assessment tools, such as LCA, as argued by Robèrt et al. [2002] and Ny et al. [2006]. However, the principles suffer from a lack of specificity and their implications are not always clear. For example, strict following of the System Conditions would mean that the human economy should be entirely biological and biodegradable [Upham 2000].

5.2 Comparison to counterfactual reference systems

According to the results of this study, the environmental impacts of a system operating as an industrial symbiosis may be smaller than in stand-alone production. In the IS Case, there are several resource and energy exchange relationships between the actors of the park, which reduce their dependence on the outside world and thereby decrease environmental impacts. In Reference Scenarios I and II, the GHG emissions of the system would grow by 40 to 75% if the current material and energy exchange links did not exist. In Reference Scenarios III and IV, environmental impacts were 5–35% higher than those of the IS Case in most of the impact categories. The reduction of the environmental impacts was primarily caused by the energy production for the town of Kouvola. All in all, the results from Reference Scenarios I–IV suggest that an eco-industrial park or an industrial symbiosis can reduce environmental impacts compared to a system in which the actors operate on their own. Nevertheless, as the large difference between Reference Scenarios I and II, on the one hand, and III and IV, on the other, shows, the way the reference scenarios are defined has a significant effect on the results. Thus, the results are very sensitive to the assumptions made.

Similar results have been obtained by Wolf and Karlsson [2008] who compared the CO_2 emissions of a hypothetical industrial symbiosis based on forest industry to a system of stand-alone plants. They found that the emissions caused by the symbiosis were smaller than in the stand-alone system. However, the case studied was hypothetical and the study only covered direct emissions of the system. Jacobsen [2006] reported similar results in his study of the Kalundborg industrial symbiosis. In the study, the savings from steam- and heat-related exchanges were compared to a hypothetical stand-alone plant using natural gas. The results showed that the symbiosis produced environmental benefits. The author concludes that from a company's point of view, industrial symbiosis should be understood in terms of individual economic and environmental performance but also as a more collective approach to industrial sustainability.

Reference Scenario V indicates that further environmental improvements could be achieved, for example, by using fly ash (produced by the power plant) as a fertiliser thereby replacing inorganic fertilisers. Moreover, replacing peat with wood at the power plant would also reduce CO_2 emissions. Another minor reduction could be achieved if the calcium carbonate plant received all the carbon dioxide it used from the pulp and paper mill instead of using liquid CO_2. However, single industrial symbioses or eco-industrial parks can only create 'islands' of sustainable development. In order to enhance global sustainability they need to organise themselves within a global network or be involved in activities on a larger regional scale [Varga & Kuehr 2007].

In addition to promoting industrial symbioses, paying attention to supply chain management could be an efficient way of advancing environmental sustainability. Moreover, supply chains are something that companies are able to promote, though not necessarily the performance of nearby companies. Resource costs have also been found to be much more significant than waste management costs, which may also provide a greater incentive for companies to work with their suppliers rather than trying to find users for their waste materials [Schliephake et al. 2009].

5.3 Uncertainties

The main uncertainties of this study were related to the data on the upstream processes. The quantity of raw materials, fuels and energy used was reported directly by the actors of the IS Case and it was fairly accurate. However, the data on upstream processes were mainly generic as they originated from different databases and did not necessarily represent the actual production processes. Thus, in the sensitivity analysis, the data sources of those upstream processes that impacted the results most were studied. In addition, the transportation distance of kaolin varied. The different scenarios resulted in fairly small changes, less than 10% in all impact categories compared with the IS Case.

One major uncertainty concerning the comparison with the counterfactual reference scenarios is that it is not clear how the stand-alone situation should be defined. Symbiotic operation is very typical of the Finnish forest industry. In this study, an attempt was made to identify a most realistic situation in terms of how the actors would operate in a stand-alone case by choosing a situation that could actually occur elsewhere. However, the choice is subjective and can be questioned. It was assumed that even in stand-alone operations, the energy production of the pulp and paper mill would be based on using the plant's own wood residues and black liquor, which is generally the case in the Finnish forest industry [e.g., Peltola et al. 2009]. The situation would have been different if we had assumed that wood was not used as an energy source at the pulp and paper mill. However, this assumption was made because it is common practice in the forest industry in Finland.

It should also be emphasised that as a method, LCA has its limitations. An LCA certainly does not take into account all the environmental impacts caused by a product or system. LCA results do not have a high temporal or spatial resolution [Udo et al. 2004]. Moreover, even though the system boundaries can, in theory, be expanded to cover the whole economic system, in practice, several generalisations have to be made. It is therefore very important to state openly the data sources and the generalisations made, and to assess the uncertainties of the study with, for example, a sensitivity analysis [see Huijbregts 2001 and Heijungs & Kleijn 2001 for a discussion on how to treat uncertainties in LCA]. Another important question when studying the environmental performance of an industrial symbiosis is how to make generalisations of any kind when the symbioses all differ from one another.

The case study in this study was based on pulp and paper production whose energy production mainly comes from renewable fuels. The results may have been different had the case study been from another industry that is more dependent on fossil fuels. For example, Chertow and Lombardi [2005] studied an industrial symbiosis system in which a coal-fired power plant used process water from nearby sources, thereby avoiding the use of freshwater withdrawals. In addition, it sold steam to an oil refinery plant and thus reduced the refinery's emissions. It was concluded that even though the system resulted in considerable decreases in SO_2, NO_X and PM_{10} emissions, it increased CO_2 and CO emissions due to the switch from oil to coal.

5.4 System boundary

In *Papers II* and *III,* the study method used was a traditional, process-based LCA, which necessarily results in upstream and downstream cut-offs. In a process-based LCA, several cut-offs are usually made due to a lack of data and other practical reasons. The selection of these cut-offs is often not explicitly stated [Suh et al. 2004, Crawford 2008]. Input-output modelling is one approach to overcome the boundaries of life cycle assessment. It allows impacts originating from production layers of infinite order to be taken into account [Munksgaard et al. 2005]. The appropriateness of the chosen system boundary is one of the key issues when considering the reliability of LCA studies, particularly comparative ones. Suh et al. [2004] even argue that selecting a system boundary that complies with ISO standards is practically impossible without input-output modelling. The combination of a process-based LCA with input-output-based data, as presented in *Paper IV,* extends the system boundary indefinitely, at least in theory. However, there are several uncertainties related to input-output data as well. Suh et al. [2004] name a few of these. Even the most disaggregated input-output tables combine products and production technologies that are highly heterogeneous in relation to environmental emissions and the materials used. Monetary value is usually used to represent inter-industry transactions, which, as a result of price differences, can result in flawed physical flow relations between industries. Moreover, in the single region domestic input-output tables, it is commonly assumed that imported commodities are produced with the same production structure and technology as on the domestic markets [for a discussion on hybrid LCA approaches, see also, e.g., Udo et al. 2004].

Crawford [2008] found that the truncation associated with process-based LCA can amount to almost 87%. It should be noted, however, that the magnitude of the truncation largely depends on how thorough the process-based LCA is. In the present study, in which particularly the energy-related flows were followed to the three orders in the supply chains, the cut-off was identified to be much smaller in most impact categories. In *Paper IV*, process-based LCA covered 80–90% of the total impacts in most impact categories, except for terrestrial ecotoxicity and metal depletion, where it covered 60% and 20% of the total impacts, respectively. Suh et al. [2004] point out that even though, in general, the hybrid analysis substantially reduces the systematic truncation problem caused by random or subjective system boundary selection in a process-based LCA, the problem of setting the boundary between the process system and the input-output system remains. If the process-based system is expanded, the resolution of the study is increased but so are the data requirements. It is therefore necessary to strike a balance when determining the boundary between the process-based and input-output part. However, the assessment is still complete as regards the upstream requirements [Suh et al. 2004]. Some simple methods have been proposed for locating the boundary between the process and input-output-based system. For example, Hondo & Sakai [2001] have developed a method based on input-output analysis to select the system boundary. Others have used structural path analysis for a preliminary ranking of the most important input flows of the studied product system [e.g., Lenzen 2002, Wood et al. 2006].

6. Conclusions

In this study the environmental benefits achieved through industrial symbiosis were assessed with a case-study symbiosis. Symbiotic exchanges reduce the need to purchase raw material and energy from outside the symbiosis. Efficient energy production and usage are critical factors that contribute to the overall environmental performance of symbiosis-like production systems. The results show that in the studied case, the symbiosis resulted in net environmental benefits in most impact categories. Additional environmental benefits could be achieved by using wood ash in forest fertilisation and treating municipal wastewaters at the pulp and paper plant.

In the IS Case, upstream processes made a considerable contribution to the overall results. Studying a symbiosis on its own and ignoring the upstream environment may therefore produce a very different picture of its environmental impacts than studies that consider upstream processes as well. When the analysis was extended with hybrid LCA, the role of upstream processes was further emphasised, indicating that the direct emissions of the IS Case actors only form a small part of the total impacts. Thus, it may be concluded that major reductions in the total environmental impacts of the system can be achieved by modifying the extraction and production of external raw materials and external energy. All in all, when assessing the environmental performance of an industrial symbiosis or an eco-industrial park, the impacts that occur upstream should also be studied, not merely the situation within the symbiosis.

LCA is a very useful, albeit labour-intensive, tool for assessing the environmental sustainability of industrial symbioses. It can also help to detect those flows whose usage could provide the greatest environmental benefits. LCA has its limitations however. Although the system boundaries can be extended to cover the whole global production system in principle, several generalisations have to be made in practice. Moreover, normalised results do not provide any information on the relative importance of the different impacts. On the other hand, the different valuation methods used in the weighing phase of life cycle impact assessment are very subjective. In addition, LCA does not consider temporal aspects.

It should be pointed out that the IS Case in this study was based on pulp and paper production, and it mainly used renewable fuels in energy production. If the case study had been based on fossil fuels, the results might have been different. One major uncertainty concerning the comparison with stand-alone production is that it is not clear how to define the stand-alone situation. In this study, four different scenarios were constructed for the stand-alone operation. The significant variations between the results of the different scenarios prove that the results are very sensitive to assumptions. Nevertheless, despite the major differences in the results, in Reference Scenarios I–IV the relative environmental impacts of the IS Case were lower than those of the reference scenarios.

It is recommended that in the future, research into industrial symbioses should also consider the upstream impacts. An input-output-based LCA could serve as a first method for a quick assessment of the environmental impacts of industrial symbioses and to locate the most environmentally important flows. The applicability of the method for this purpose should be studied further. Moreover, in order to gain more knowledge on the real life cycle environmental benefits of industrial symbioses, similar studies on different kinds of symbioses are needed.

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Appendix A: Data sources and data for the unit processes of the system

Data has been categorised according to the actors of the IS Case. Data that has been compiled within this study is given in the table. For data that has been taken from LCA databases, only reference to the relevant database is made.

Raw materials and energy processes of the ClO_2 plant								
Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
Chemicals								
Borax, anhydrous, powder, at plant	Swiss Center for Life Cycle Inventories, 2007	2007						
Nitrogen, liquid	Swiss Center for Life Cycle Inventories, 2007	1997						
Sodium hydroxide	Swiss Center for Life Cycle Inventories, 2007	2000						
Hydrochloric acid	Swiss Center for Life Cycle Inventories, 2007	1997						
Electricity and fuels								
Electricity, average Finnish	Dahlbo et al., 2005	average of 2000–2002	oil	121 053	kg	*Emissions to air*		
			coal (in ground)	2 070 420	kg	As	0,1	kg
			natural gas (in ground)	971 990	kg	CO_2, fossil	10 603 800	kg

	oil (in ground)	83 129	kg	Cd	0,0	kg
	uranium ore	428	kg	CH_4	9 655	kg
				CO	688	kg
				Cu, air	0,2	kg
				Hg, air	0,2	kg
				N_2O	301	kg
				Ni	1	kg
				NO_X	20 014	kg
				NMVOC	61	kg
				particles	2 573	kg
				Pb	0,9	kg
				SO_2	16 665	kg
				V, air	2,6	kg
				Zn	0,4	kg
				Emissions to water		
				Cr, water	0,3	kg
				N, tot	54	kg
				NH_4	30	kg
				NO_3	15	kg
				P, tot	2,0	kg
				Energy		
				Electric power	52 800	MWh

Raw materials and energy inputs for the local energy plant								
Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
Electricity and fuels								
Production of natural gas, production in Russia, high distribution network in Finland	Swiss Center for Life Cycle Inventories, 2007	2000						
Production of electricity and heat from natural gas in a Finnish plant	VAHTI database	2005	natural gas	1,83E+08	MJ	*Emissions to air*		
						CO_2, fossil	1,02E+07	kg
						NO_X	15 700	kg
electricity, hydropower, average Finnish production	Swiss Center for Life Cycle Inventories, 2007	2000						

Raw materials and energy inputs for the municipal wastewater treatment plant								
Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
Chemicals								
PIX-105 chemical	Kemira Oy 2000a, Kemwater, EPD for PIX-105	2000						
Polyaluminium chloride	Kemira Oy 2000b, Kemwater, EPD for PAX-18 chemical	2000						
Electricity and fuels								
Heat, average Finnish production	Nissinen, A., personal communication	2002	natural gas	30	GJ	*Emissions to air*		

			peat	18	GJ	CH_4	17	kg
			coal	22	GJ	CO	10	kg
			oil	7	GJ	CO_2, fossil	6 410	kg
						N2O	1	kg
						NMVOC	0	kg
						NOx	11	kg
						particles	13	kg
						SO2	12	kg
						Energy		
						Heat	79	GJ
Electricity, average Finnish production	See ClO_2 plant							

Raw materials and energy inputs for the calcium carbonate plant

Material/energy flow	Source	Year	Inputs	Unit	Output	Unit
Chemicals						
Phosphoric acid	Swiss Center for Life Cycle Inventories, 2007	1990–1994				
Calcium oxide	Swiss Center for Life Cycle Inventories, 2007	2000				
CO_2, liquid	Environmental permit of Oy Aga Ab Kilpilahti plant and VAHTI database	2006	*Energy*		*Chemicals*	

			electric power	725	MWh	CO_2, liquid	2 110 000	kg
Electricity and fuels								
Electricity, average Finnish generation	See ClO_2 plant							

Raw materials and energy inputs for the hydrogen peroxide plant						
Material/energy flow	Source	Year	Inputs	Unit	Output	Unit
Chemicals						
Unspecified organic solvents	Swiss Center for Life Cycle Inventories, 2007	2000				
Acetic acid	Swiss Center for Life Cycle Inventories, 2007	1997				
Electricity and fuels						
Natural gas	See local energy plant					
Electricity, average Finnish generation	See ClO_2 plant					
Heat, average Finnish production	See municipal wastewater treatment plant					

Raw materials and energy inputs for the power plant								
Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
Chemicals								
Sodium hydroxide	See ClO_2 plant							
Sulphuric acid	Swiss Center for Life Cycle Inventories, 2007	2001						
Hydrochloric acid	See ClO_2 plant							
Electricity and fuels								
Light fuel oil	Swiss Center for Life Cycle Inventories, 2007	1989–2000, most information for 2000						
Natural gas	See local energy plant							
Mining of peat	Environmental permit of the VAPO Karhusuo site, Vahti database and Leijting 1999	End of 1990s and 2000, 2005	*Fuels*			*Emissions to air*		
			light fuel oil	158 589	kg	CO_2, fossil	3,7E+06	kg
			Resources			CH_4	4,2E+03	kg
			Peat, in ground	6,99E+07	kg	*Emissions to water*		
						N, tot	2,0E+03	kg
						P, tot	5,9E+01	kg
						Fuels		
						peat	7,0E+07	kg

Heat, average Finnish production	See municipal wastewater treatment plant			
Electricity, average Finnish generation	See ClO_2 plant			
Materials				
Wood chips, mixed, from industry	Swiss Center for Life Cycle Inventories, 2007	2002		
Wood residuals, mixed, at forest	Swiss Center for Life Cycle Inventories, 2007	1996		

Raw materials and energy inputs for the pulp and paper mill

Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
Chemicals								
AKD sizer	Swiss Center for Life Cycle Inventories, 2007	2000						
Aluminium sulphate	Swiss Center for Life Cycle Inventories, 2007	1995						
Biocides, unspecified	Swiss Center for Life Cycle Inventories, 2007	2000						
Calcite sludge	Environmental permit of Suomen Karbonaatti Oy and VAHTI database	2006	*Chemicals*			*Materials/Products*		
			$CaCO_3$	1,29E+08	kg	calcite sludge	1,78E+08	kg
			electric power, average Finnish	38 886	MWh			

Mining of $CaCO_3$	Environmental permit of Nordkalk Oy and VAHTI database	Materials and energy inputs 2006, emissions and waste 2003	*Energy*			*Emissions to air*		
			electric power	8 805	MWh	CO_2, fossil	2,59E+07	kg
			heat energy	1 070	GJ	NOx	54 505	kg
			Fuels			particles	7 050	kg
			hard coal	4,29E+06	kg	SO2	14 423	kg
			natural gas	2,81E+06	MJ	*Emissions to water*		
						N, water	267	kg
						P, tot	8,67	kg
						Materials/Products		
						$CaCO_3$	1,29E+08	kg
CO_2, liquid	See Calcium carbonate plant							
Fatty acids	Swiss Center for Life Cycle Inventories, 2007	1995						
Kaolin	Swiss Center for Life Cycle Inventories, 2007	2000						
Latex	Environmental permit of Dow Finland and VAHTI database	2005	*Fuels*			*Emissions to air*		
			light fuel oil	134 933	kg	CO_2, fossil	1,39E+06	kg
			natural gas	1,67E+07	MJ	NOx	1 204	kg
						Materials/Products		
						latex	3,39E+07	kg

Magnesium sulphate	Swiss Center for Life Cycle Inventories, 2007	2000						
Modified starch	Environmental permit of Ciba Specialty Chemicals Oy and VAHTI database	2005	*Energy*			*Emissions to air*		
			electric power	5 885	MWh	CO_2, fossil	2,24E+06	kg
						NOx	3 431	kg
						particles	46,5	kg
						SO2	11,6	kg
						Emissions to water		
						N, tot	4 167	kg
						P, tot	1 964	kg
						Materials/Products		
						modified starch	3,33E+07	kg
Optical brighteners	Swiss Center for Life Cycle Inventories, 2007	2000						
Oxygen, liquid	Swiss Center for Life Cycle Inventories, 2007	1997						
Phosphoric acid	See calcium carbonate plant							
Polyaluminium chloride	See municipal wastewater treatment plant							
Potato starch	Swiss Center for Life Cycle Inventories, 2007	2002						
Propane/butane	Swiss Center for Life Cycle Inventories, 2007	1980–2000						
Calcium oxide	See calcium carbonate plant							

Retention aids	Swiss Center for Life Cycle Inventories, 2007	2000						
Sodium hydroxide	See ClO_2 plant							
Sodium sulphate	Swiss Center for Life Cycle Inventories, 2007	2000						
Sulphur dioxide	Swiss Center for Life Cycle Inventories, 2007	1997						
Sulphuric acid	Swiss Center for Life Cycle Inventories, 2007	2001						
Talc	Environmental permit of Mondo Minerals, Outokumpu mine and enrichment plant, and VAHTI database, 2007	2007	*Energy*			*Chemicals*		
			electric power	1 372	MWh	talc	2,23E+06	kg
			Fuels			*Emissions to air*		
			heavy fuel oil	105 479	kg	CO_2, fossil	356 442	kg
						Nitrogen oxides	1 142	kg
						particles	299	kg
						Sulfur dioxide	1 895	kg
						Emissions to water		
						As, water	10,4	kg
						Ni, water	9,9	kg
						Materials/Products		
						nickel unspecified	46 782	kg

Urea	Swiss Center for Life Cycle Inventories, 2007	1999						
Electricity and fuels								
Heat, average Finnish production	See municipal wastewater treatment plant							
Electricity, average Finnish generation	See ClO_2 plant							
Hardcoal	Swiss Center for Life Cycle Inventories, 2007	1977–1989						
Heavy fuel oil	Swiss Center for Life Cycle Inventories	1980–2000, most data for 2000						
Natural gas	See local energy plant							
Materials								
Hardwood, Scandinavian, under bark	Swiss Center for Life Cycle Inventories, 2007	2000						
Scandinavian softwood, under bark	Swiss Center for Life Cycle Inventories, 2007	2000						
Sulphate pulp, bleached	Sunila Oy, 2004		*Energy*			*Emissions to air*		
			electric power, average Finnish production	16 198	MWh	CO_2, fossil	4,84E+06	kg
			Fuels			Nitrogen oxides	72 485	kg
			light fuel oil	79 709	kg	particles	37 690	kg

Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
			natural gas	8,27E+07	MJ	Sulfur dioxide	4 492	kg
						Emissions to water		
						Nitrogen	2 754	kg
						P, tot	915	kg
						Materials/Products		
						sulphate pulp	3,49E+07	kg
Woodchips, softwood	Swiss Center for Life Cycle Inventories, 2007	1996–2002						

Avoided impacts						
Material/energy flow	Source	Year	Inputs	Unit	Output	Unit
Materials						
Chain oil	Fortum Oil and Gas Oy 2002	2002				
Corrugated board	Swiss Center for Life Cycle Inventories, 2007	1995–2000				
Mining of rocks	IISI 1998	1998				
Mining of iron	Swiss Center for Life Cycle Inventories, 2007	1998				
Limestone production	Swiss Center for Life Cycle Inventories, 2007	Mining 1992, other data 2000				
Woodchips	Swiss Center for Life Cycle Inventories, 2007	1998				

Waste management processes

Material/energy flow	Source	Year	Inputs		Unit	Output		Unit
Waste management processes								
Hazardous waste disposal	Ekokem Oy, 2007	2007	Hazardous waste, mixed	85 670	kg	*Emissions to air*		
						CO_2, fossil	137 072	kg
						CO	10,3	kg
						HCl, air	1,71	kg
						HF	0,05	kg
						Hg, air	0,86	kg
						Nitrogen oxides	94,2	kg
						particles	0,9	kg
						PCDD, PCDF	1,71E-05	g
Inert material landfill	Swiss Center for Life Cycle Inventories, 2007	1995						
Municipal waste landfill	Pelkonen et al. 2000	End of 1990s	*Energy*			*Emissions to air*		
			electric power	0,375267	MWh	CO_2, fossil	1 390	kg
			Fuels			CH4	13 625	kg
			diesel oil	0,353945	kg	NO_X	12,4	kg
						SO_2	0,85	kg
						Emissions to water		
						Cd, unspecified	0,0090	kg

					Cr, unspecified	0,034	kg
					Lead, unspecified	0,006	kg
					Mercury	0,00060	kg
					NH4 as N	83,6	kg
					Nickel, unspecified	0,11	kg
					P, tot	0,15	kg
					Zn, unspecified	0,043	kg

Transport processes						
Material/energy flow	Source	Year	Inputs	Unit	Output	Unit
Transport processes						
Electric train	LIPASTO calculation system and Dahlbo et al. 2005	2000–2002				
Diesel train	LIPASTO calculation system and Swiss Center for Life Cycle Inventories, 2007	2000				
Full-trailer timber truck	LIPASTO calculation system & Swiss Center for Life Cycle Inventories, 2007	2006				
Full-trailer combination truck	LIPASTO calculation system & Swiss Center for Life Cycle Inventories, 2007	2006				
RO-RO ship	LIPASTO calculation system & Swiss Center for Life Cycle Inventories, 2007	1999				

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Appendix B

Papers I–IV

PAPER I

How can the sustainability of industrial symbioses be measured?

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How can the sustainability of industrial symbioses be measured?

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Abstract: In the scientific literature, there are (so far) few studies quantifying the environmental benefits or sustainability of Industrial Symbiosis (IS) networks although, at the same time, the potential tools for these kinds of assessments have been developed rapidly both in number and capacity. In this article, we first review the existing studies on the environmental performance of IS systems. We draw a conclusion that these studies usually only concentrate on one or a limited number of factors and also use a narrow approach to system boundaries considering just the impacts taking place within the symbiosis. Finally, we suggest that The Natural Step (TNS) System Conditions could constitute a basis which – through a set of sustainability criteria and a series of questions derived from them – would essentially steer the analyses made about the environmental performance and overall sustainability of the IS network at hand.

Keywords: industrial symbiosis; industrial ecology; system boundaries; sustainability principles; The Natural Step; TNS; environmental performance; environmental management; tools; Kymenlaakso; Finland.

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Ari Nissinen works as a Senior Researcher at the Research Programme for Production and Consumption of SYKE, Finland. He finalised his PhD from the University of Helsinki in 1999 and has worked in SYKE since 2001. His work covers a wide range of integrated product policy instruments, including greener public purchasing, product panels, eco-labels and communication about life cycle assessments.

1 Introduction

Industrial Symbiosis (IS), a central concept of Industrial Ecology (IE), studies the physical flows of materials and energy in local systems (Wolf *et al.*, 2007; Korhonen *et al.*, 2002; Chertow, 2000; Côte and Cohen-Rosenthal, 1998; Erkman, 1997). A core idea of the concept is that companies are part of chains of suppliers and consumers, which resemble those of natural ecosystems. To ensure their productivity and be able to survive, companies depend on the resources available in the environment. An ideal IS utilises the waste materials and energy between the actors of the system and thereby reduces virgin material and energy inputs and waste and emissions outputs (Chertow, 2000). An IS can also include the exchange of information or services such as logistics (Mirata and Emtairah, 2005).

Although several examples of IS-type arrangements have been described in the literature, there has been a lack of quantitative assessment of the overall environmental or sustainability performance of symbioses (Wolf, 2007; Albino *et al.*, 2003). At the same time, several methods have been developed within IE to quantify and analyse societal material and energy flows, such as Life Cycle Assessment (LCA) (*e.g.*, Udo de Haes and Heijungs, 2007), Material Flow Analysis (MFA) (*e.g.*, European Commission, 2001), environmental input-output accounting (Bailey *et al.*, 2004), ecological footprint analysis (*e.g.*, Bagliani *et al.*, 2008; Holmberg *et al.*, 1999) and material intensity per service unit (*e.g.*, Wuppertal Institute, 2007). However, so far, only few studies have applied these tools to the specific features of IS.

In this study, we use the term 'sustainability' because the focus is on social sustainability, in addition to environmental sustainability. Economic sustainability is not considered, but we believe that economic viability is a precondition for companies to enter symbiotic arrangements and will, therefore, be accounted for as well.

The existing quantitative studies on the environmental performance of IS are first reviewed in Section 2. However, quantitative measures are not enough when analysing the overall environmental or sustainability performance of industrial systems. We believe that what is needed is an overall framework in which quantitative analysis is combined with qualitative analysis. Therefore, we propose using a framework following the methodology presented by Robèrt *et al.* (2002; see also Robèrt, 2000; Holmberg and Robèrt, 2000; Robèrt *et al.*, 2001; Ny *et al.*, 2006), which would bridge the gap between qualitative and quantitative studies. The framework is presented using an ongoing case study in Section 3. Finally, the main findings of the article are discussed and the concluding remarks are presented in Section 4.

2 Studies on the environmental benefits of industrial symbioses

In the scientific literature, so far, few studies have quantified the environmental (or sustainability) performance of IS networks. Examples include Keckler and Allen (1999), who studied the applicability of water distribution modelling techniques to water management in an industrial park. The approach was used to demonstrate the possibilities of enhancing water reuse among the different companies in the park. In the case study, several economical water reuse opportunities could be found. The authors suggested that such opportunities may exist for other networks of companies as well. Moreover, similar models could be applied for modelling the reuse of other materials, too.

Chertow and Lombardi (2005) quantified the economic and environmental costs and advantages of symbiosis partners in Guayama, *i.e.*, a symbiosis network in Puerto Rico. The study concluded that the participating organisations receive substantial economic and environmental benefits from participating in the symbiosis, but the benefits are unevenly distributed. According to the authors, it is likely that similar benefits are found in other comparable situations as well.

Kurup *et al.* (2005) presented a method to identify and report all the positive and negative consequences of three IS projects located in Kwinana, Australia. The approach is based on indicators and it attempts to take into account all the economic, social and environmental impacts caused by the symbioses. However, the approach is mainly qualitative and consists of listing the potential impacts and estimating their size on a scale from minor to major. According to the authors, economic indicators should include the direct and indirect costs of the project, the costs avoided through the project and any profit received from selling the byproduct material, energy or water. Within all the impact categories, the authors emphasised that the avoided impacts should also be included in the analysis.

Onita (2006) conducted a literature survey on 19 documented IS. Based on the published reports on these symbioses, he collected data on water, energy and material savings and reductions of solid waste and emissions in each of the cases. The results showed that reductions had been achieved through the symbiosis arrangement. Moreover, the results strongly supported the ‘anchor tenant’ principle often used when describing IS.[1]

Brings Jacobsen (2006) studied some of the central symbiotic exchanges, mainly water and steam, of the Kalundborg IS. He chose these two exchanges for the in-depth study as they illustrate a typical IS business practice based on geographical closeness, byproduct reuse and the optimisation of resource use. For steam and heat-related exchanges, the savings were compared to a hypothetical stand-alone plant using natural gas. The study showed that both significant and less significant environmental benefits were achieved as a result of substitution, utility sharing and water/energy cascading. However, there was also potential for further optimisation. The analysis indicated that the IS exchanges only form one element in the whole process of improving the environmental performance of a number of companies. Therefore, it should not be regarded as an ultimate solution, but as a part of a process of decreasing the total environmental impact of the individual company.

In the UK, an integrative framework documenting the benefits of IS has been developed within the UK National Industrial Symbiosis Programme (NISP) (Agarwal and Strachan, 2006). Within the programme, information on over 100 case studies has been collected so far. The NISP sees the documenting of IS cases as an effective way to provide evidence of the economic, environmental and social benefits of symbiosis participation. For example, in 2005/2006, the programme reported over 600 000 tonnes of waste diverted from landfills and over 300 000 tonnes of CO_2 savings (Agarwal and Strachan, 2006).

Salmi (2007) studied the link between IS and increased eco-efficiency in the mining industry of the Kola Peninsula in Northwest Russia. A complex utilisation model was developed by the authorities for the region in the 1980s. However, due to the collapse of the Soviet Union, the model was never implemented on a full scale. As the model is analogous to IS, Salmi used it to study the region's hypothetical eco-efficiency development between the years 1985 and 2005 and compared the results to the actual development of the area (*i.e.*, without 'complex utilisation'). The results indicate that complex utilisation would have resulted in increased eco-efficiency, but not all environmentally harmful emissions would have decreased. As a consequence of the Soviet Union's collapse and the introduction of upstream pollution prevention and more advanced emission reduction technologies, similar reductions were also achieved in the actual system. The author argued that in systems such as the mining industry in Kola Peninsula, where the production volumes are high and the environmental management techniques are poorly developed, higher decreases in emissions and waste flows may be achieved with upstream pollution prevention combined with traditional end-of-pipe technologies than with IS introduction.

Sendra *et al.* (2007) applied the MFA methodology to an industrial area called Santa Perpètua de Mogoda in Spain. The area is one of the most industrialised towns near Barcelona. There are more than 500 businesses in the area, 40 of which were analysed in the study. MFA-based indicators, complemented with water and energy indicators, were used to evaluate how the area could be transformed into an eco-industrial park, *i.e.*, to an IS. The paper provides a thorough description of how to adapt MFA for an industrial park or region. In the analysis, the whole area was treated as one system corresponding to a national economy used in traditional MFA and raw materials and products from outside the area were treated as imports. Correspondingly, the products and materials sold outside the system boundaries were considered exports. However, while in nationwide MFA, the system is treated as a black box, in this study, the material flows of the individual companies were also analysed. The authors argued that in this way, the possibilities to improve the system's performance can be detected better. They also concluded that MFA-based indicators should be complemented with indicators on water and energy. In the case study, the material efficiency in manufacturing was the opposite of a product's added value in the chemical sector. This means that in the case study companies, the high value of the products economically sustains the high material inefficiency. Respectively, material optimisation seemed to be higher in the products with less added value. However, the authors emphasised that these findings need further studies before being generalised.

Wolf (2007) compared the different tools for environmental systems analysis and energy systems analysis and their applicability for an IS. She studied the environmental impact of a hypothetical forest industry system using an optimisation method based on mixed integer linear programming. The system's CO_2 emissions were compared to those of a system consisting of stand-alone plants. The results indicated that the environmental impacts of an IS can be smaller than those of a system consisting of individual plants. However, the study only covered the CO_2 emissions of a hypothetical system and the results are, therefore, only indicative.

Singh *et al.* (2007) studied an agro-chemical complex consisting of 13 chemical and petrochemical industries in Mississippi. In their study, the system was reconfigured for utilising surplus CO_2. This meant adding several new actors in the complex. Both of these design schemes were analysed with an LCA-type environmental impact assessment. The conducted LCA was a so-called ‘entry to exit’ study, *i.e.*, only the materials used inside the complex were considered. Raw material production or waste treatment was not taken into account. The authors concluded that LCA is a highly useful tool for analysing and comparing different designs of IS. According to them, a comprehensive LCA should be conducted before starting a new eco-industrial park in order to assess the potential advantages and disadvantages of the system and thereby select the best design option from the sustainable development point of view.

As our review shows, some studies worldwide have also attempted to quantitatively analyse the environmental (sustainability) aspects of IS. Most of them, however, only concentrated on one or a limited number of factors, mostly material and energy flows, or on just the flows occurring inside the symbiosis (Singh *et al*., 2007). The approach we are proposing differs from these studies in that we suggest using The Natural Step (TNS) System Conditions (*e.g.*, Robèrt *et al.*, 2002; see Section 3) as a basis of the analysis and building the analysis and methods used on them.

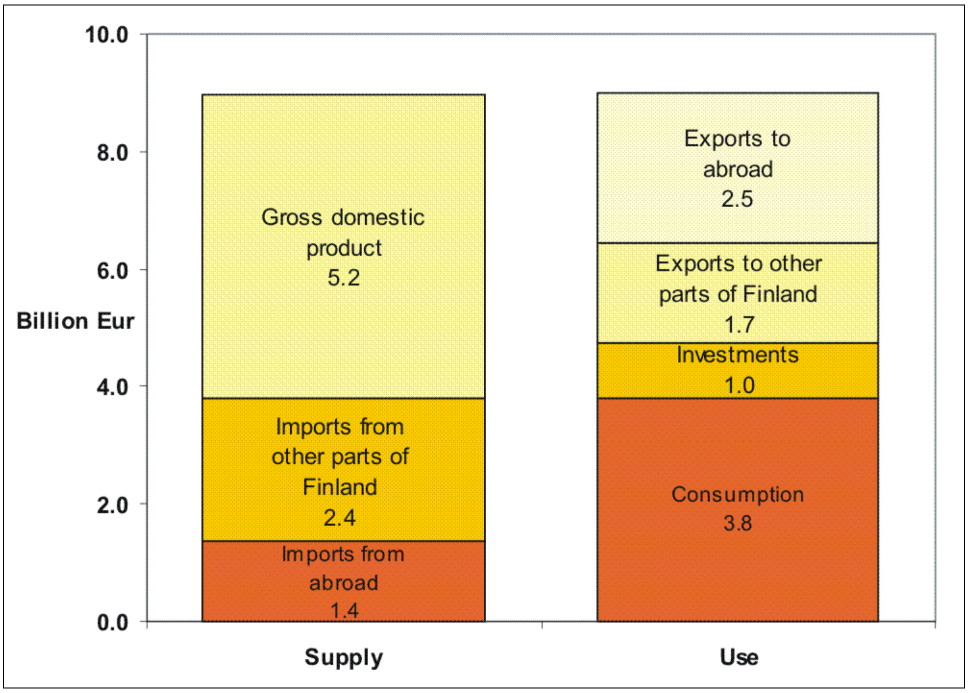
3 A framework for the analysis of industrial symbioses

In this section, we suggest a new framework for analysing the sustainability performance of IS systems based on TNS System Conditions. In order to illustrate the approach, we will present a project titled ‘Industrial Symbiosis System Boundaries (ISSB)’. The project will be carried out in 2007–2010 by the Finnish Environment Institute (SYKE) and the Åbo Akademi University (ÅA). In the project, the IS concept will be analysed both conceptually and empirically. The ultimate aim of the project is to assess and develop approaches through which the environmental and overall sustainability performance of IS can be evaluated.

3.1 A case study: the 2007–2010 ISSB project

In the project, the highly industrialised Kymenlaakso region in Finland will be used as a study area. Here, we build upon the results of a life environment project named ‘The Eco-efficiency of Regions – Case Kymenlaakso (ECOREG) 2002–2004’.[2] Kymenlaakso is situated in South-Eastern Finland, next to the Russian border. Due to its location and industrial structure, the region is strongly linked to the national and global economic system through trade (Figure 1). The core of the business economy is the strong pulp and paper industry and the subcontracting and service businesses that have evolved around it, including especially logistics services. In the beginning of the 2000s, the forest industry made up more than one-fourth of the value-added of the regional economy and more than 60% of the secondary production (Mäenpää and Mänty, 2004).

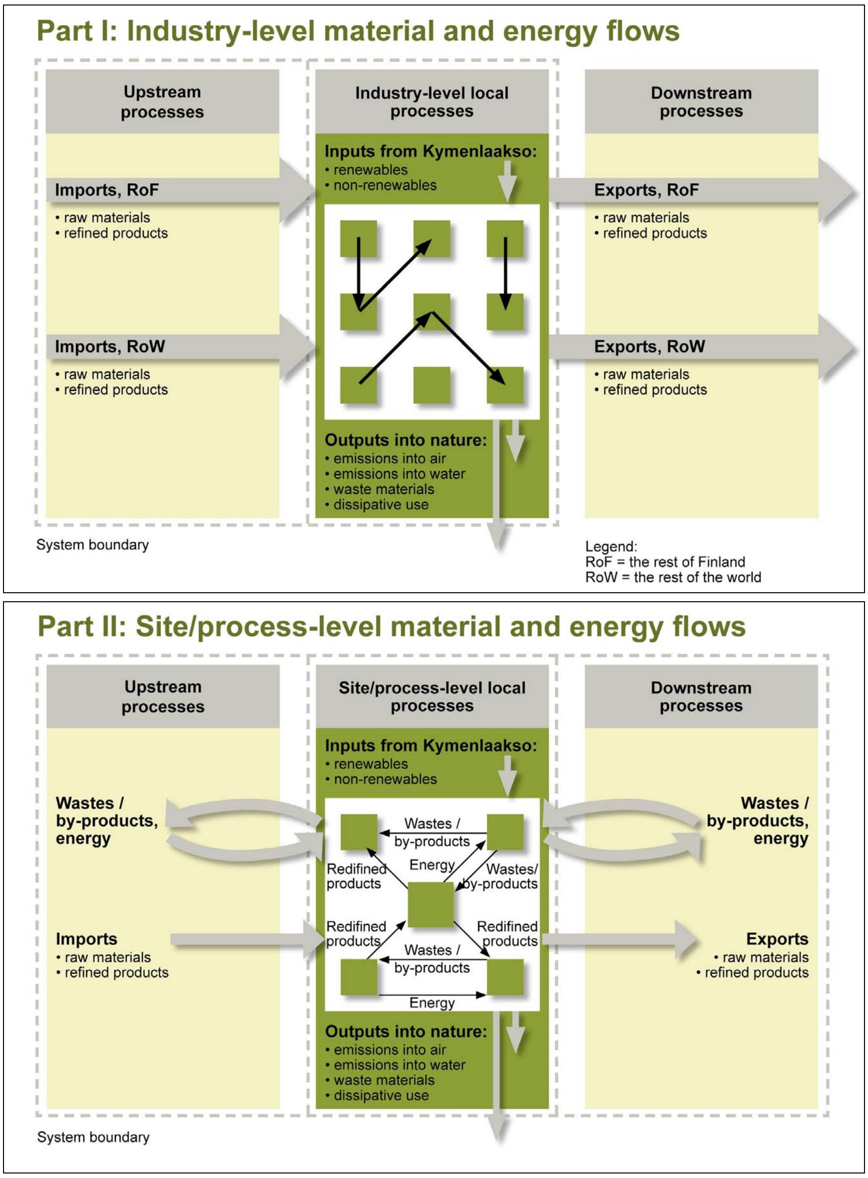
Figure 1 The supply and use balance of monetary product flows in the economy of Kymenlaakso in 2002 (see online version for colours)



Source: Statistics Finland (2006)

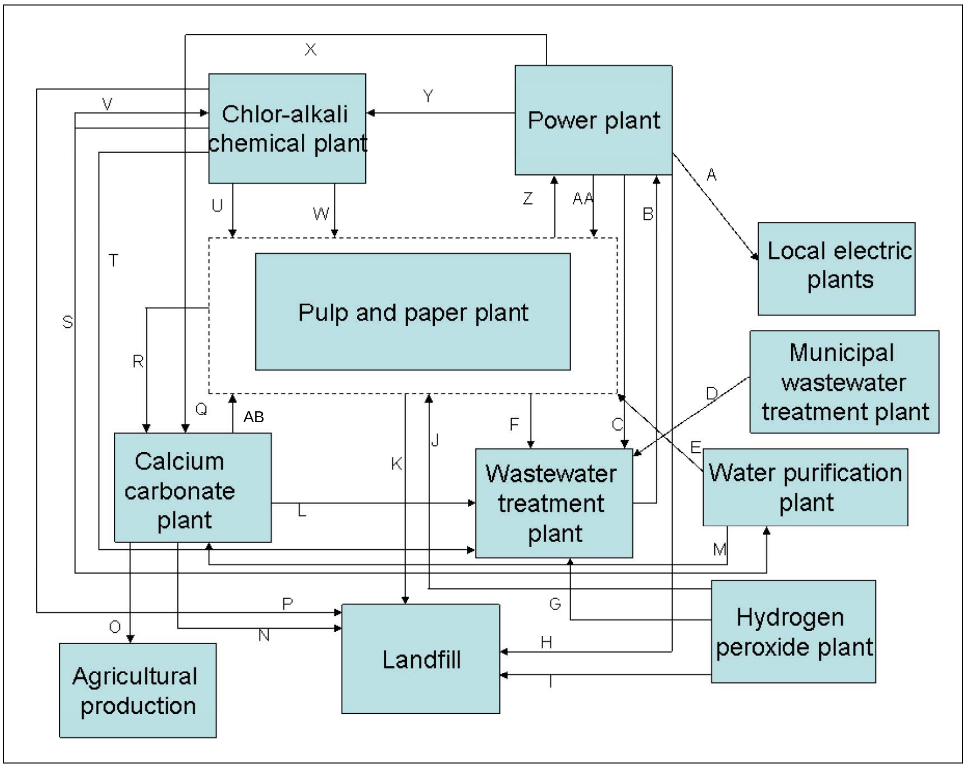
In the ISSB project, a physical industry-level (sector-level) input-output table will first be constructed for Kymenlaakso for 2005 (the latest year possible at this stage), updating the year 2000 figures of the ECOREG project (Figure 2, Part 1) and used for identifying the potential IS-type activities in the region. One IS is then chosen for an in-depth case study. The sector-level input-output table is disaggregated and transformed into a site/process-level input-output matrix depicting the interdependencies in materials and energy flows among the anchor tenant (cf. Section 2) and the other actors of the case IS network (Figure 2, Part 2). Figure 2, Part 1 illustrates the system boundaries (upstream + industry-level local processes) and the factors included in Kymenlaakso's industry-level physical input-output analysis in the ECOREG project. The squares inside the Kymenlaakso box (white area) stand for industries or economic sectors (agriculture, forestry, mining, forest industry, *etc.*; also stand for private and public consumption and investments). Part 2 illustrates the site/process-level input-output analysis of the ISSB project. The white area in the Kymenlaakso box represents the local IS of the in-depth case study. The square in the centre stands for the anchor tenant and the other squares stand for the other players of the IS (in the figure, the upstream and downstream links are connected to the whole IS system; in reality, of course, the links may tie any of the individual local symbiosis actors to upstream and downstream processes).

Figure 2 Transforming the Kymenlaakso industry-level input-output analysis (Part 1) into a site/process-level input-output analysis (Part 2) (see online version for colours)



An industrial park that has developed around the UPM-Kymmene, Kymi pulp and paper plant in the town of Kuusankoski, Kymenlaakso region, will be used as a case study symbiosis (Figure 3). In addition to the pulp and paper plant, the park consists of three chemical plants, one power plant, a water purification plant, a sewage plant and a landfill. The park also has close interaction with regional energy suppliers (the symbiosis' power plant sells electricity and district heat to the energy suppliers), a communal sewage plant (the sewage plant of the symbiosis receives sludge from the communal plant) and local agricultural production (through the application of lime in the fields). The pulp and paper plant was established in 1872 and has operated since then. Thus, in addition to the present situation, the evolution of the system will also be analysed in the project.

Figure 3 The in-depth case study symbiosis: 'Kymi eco-industrial park' (see online version for colours)



Notes: A – district heat and electricity; B – sewage sludge; C – wastewater; D – sewage sludge; E – water; F – wastewater; G – wastewater; H – ash; I – miscellaneous waste; J – hydrogen peroxide (H_2O_2); K – miscellaneous waste; L – wastewater; M – water; N – miscellaneous waste; O – lime; P – miscellaneous waste; R – carbon dioxide (CO_2); S – chlorine (Cl_2); T – wastewater; U – chlorine dioxide (ClO_2); V – water; W – sodium hydroxide (NaOH); X – steam, electricity; Y – steam; Z – biomaterials used as fuel; AA – steam, electricity, heat; AB – calcium carbonate (CaCO3).

3.2 TNS System Conditions as guiding principles

Karl-Henrik Robèrt, together with his colleagues, has in recent years done insightful pioneering work on the principles for sustainability (Holmberg *et al.*, 1996; Holmberg and Robèrt, 2000; Robèrt, 2000; Robèrt *et al.*, 2002; Ny *et al.*, 2006). The basic sustainability principles they formulated are at present known as TNS System Conditions.

Within the TNS context, four system conditions were determined that apply to *ecological* and *social* sustainability (Robèrt *et al.*, 2002, p.198; Ny *et al.*, 2006, p.64).

In sustainable society, nature is *not* subject to systematically increasing:

1. concentrations of substances extracted from the Earth's crust
2. concentrations of substances produced by society or
3. degradation by physical means.

In addition, the system condition for *social* sustainability requires that, in that society:

4. people are *not* subject to conditions that systematically undermine their capacity to meet their human needs.[3]

We believe that these system conditions could form a basis for evaluating IS systems with the aim of finding answers to the following fundamental question:

> "What is the contribution of an individual local IS system to the overall global objective of sustainability?"

IS systems are something that usually start as motivated by (mostly) economic gains among individual industrial actors who begin to exchange waste materials and waste energy with each other, thus forming an 'IS' or an 'eco-industrial park'. An essential feature of these IS systems is that they are not static – instead, they have a tendency to evolve in space and time, as well as in other respects. It is within this context that the application of conceptual sustainability principles, such as TNS System Conditions, can make a crucial contribution to decision making, revealing the (existing or suggested) actions that are in conflict with the global objective of sustainability.

TNS System Conditions are based on the principle of back casting (*e.g.*, Robèrt *et al.*, 2002; Ny *et al.*, 2006). Back casting refers to a planning methodology in which a simplified desired outcome is first envisioned. After this, plans are made step by step on how to reach this outcome. This approach radically differs from the presently prevailing approach, in which the discussion often focuses on the short-term problems and consequences of the different alternatives, thereby forgetting the overall goal, *e.g.*, sustainability.

3.3 Combining qualitative and quantitative appraisals

Building on TNS thinking, we propose the procedures described in Figures 4 and 5 and Table 1 as a basis for analysing the dimensions of IS systems. An IS system has implications on three spatial levels: local, regional and global. TNS System Conditions 1–4 are valid for each of these levels. In Table 1, the basic TNS System Conditions are interpreted from an IS point of view and transformed into an 'IS System Condition Analysis'. As a first step, the questions of the type listed in the table can be asked. They aim to screen the most critical issues and practices from the system condition perspective. It should be noted that the list in Table 1 is a 'generic' list of questions prepared by developing and applying the thinking found in Robèrt *et al.* (2002). The specific characteristics of each local IS system steer the setting of more detailed questions in practice. As pointed out by Holmberg *et al.* (1999), the tools for monitoring sustainability are only useful if they are founded on a clear definition of sustainable development.

Table 1 IS system condition analysis: the key questions to be asked

System condition 1	*System condition 2*	*System condition 3*	*System condition 4*
Does the IS *systematically* contribute to:	Does the IS *systematically* contribute to:	Does the IS *systematically* contribute to:	Does the IS *systematically* contribute to:
1 reducing the throughput of minerals that are scarce in nature? 2 more eco-efficient use of extracted materials? 3 reducing the dependence on fossil fuels?	1 substitution of substances that are persistent and nondegradable in nature? 2 more eco-efficient use of produced materials/products?	1 phasing out destructive patterns of interference with the ecosystems? 2 extracting resources from well-managed ecosystems only? 3 favouring less area-consuming activities?	1 reducing risks to human health caused by the pollution of the environment? 2 preserving resources for future generations (through systematic dematerialisation and substitution)? 3 not undermining the living conditions of the world's poor people?

Note: IS has impacts on the regional and global levels through supply chains. The questions were derived by developing and applying the ideas presented in Robèrt *et al.* (2002).

The IS System Condition Analysis – and its questions (Table 1) – sets a steering framework for the in-depth ISSB case study (Figure 4). It can provide the specific research questions to be asked and give guidance on which methods to use in the analysis. For example, in the case study, the possible research questions include: does the IS replace fossil fuels with biofuels (System Condition 1) or does the IS use timber only from well-managed forests (System Condition 3)?

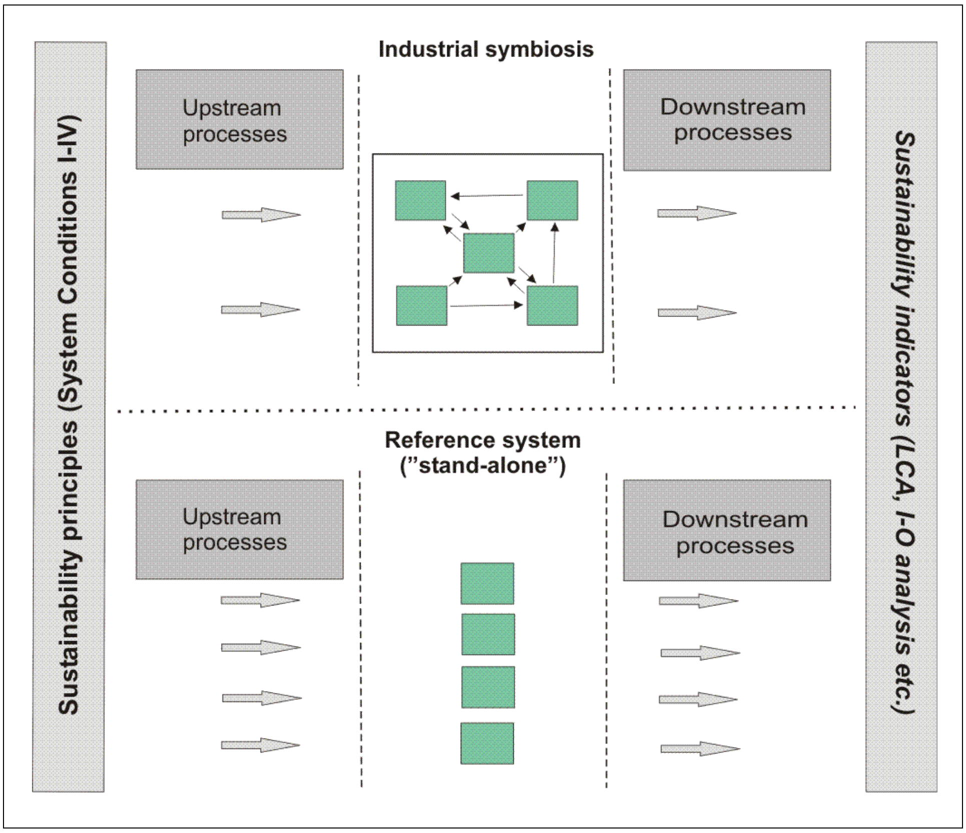
The *quantitative analysis* will then be made through the following steps:

Step 1 The local environmental burden of the system (resource use, emissions and wastes) is first analysed quantitatively.

Step 2 The analysis is then expanded in order to study, the impacts of the system in a wider – regional/national and global – context. Different methods will be considered for the analysis of these impacts – LCA, environmental input-output analysis and hybrid LCA,[4] Social Life Cycle Assessment (SLCA) (see UNEP-SETAC Life Cycle Initiative, 2006; Weidema, 2005; Dreyer *et al.*, 2006; ISO 14040, 2006), Social Impact Assessment (SIA) (see Becker, 2001; UNEP, 2003) and Risk Assessment (RA) (ecological and human risks; see *e.g.*, Landcare Research, 2007).

Step 3 Lastly, the outcome of the first three steps is compared to the picture portrayed by a reference system – consisting of 'stand-alone plants' (Figure 4) – that will offer an important insight into the (real) symbiosis benefits from a wider sustainable development point of view. The purpose is to find out what the impacts of the actors would be without the symbiosis connections. This way, the possible benefits from participating in the symbiosis can be appraised.

Figure 4 The sustainability principles (System Conditions 1–4 and questions in Table 1) steer the assessment of the sustainability performance of the case study symbiosis (see online version for colours)



Note: Sustainability indicators, based on the use of methods such as LCA, input-output analysis, *etc.*, are used for quantification.

Partially, however, only *qualitative appraisals* are possible for answering the questions in Table 1. For example, it is usually relatively straightforward to get data on the main raw materials used and the emissions produced. However, there are several trace emissions of which we may know nothing about. Moreover, data on land use and ecosystem destruction (especially on regional and global level) may be difficult to obtain.

A variety of tools and metrics are available for an analysis like the one suggested in Table 1. Some of the most obvious and potential tools were mentioned above and are compiled in Table 2. As pointed out by, *e.g.*, Byggeth *et al.* (2007), instead of developing more new tools, the applicability and compatibility of the existing ones to new uses should be studied. Thus, our aim is to test their applicability in the case study IS system.

However, it should be emphasised here that the proposed methods (such as LCA) also have their limitations. An LCA certainly does not take into account all the environmental impacts caused by a product or system. In addition, although the system boundaries can, in theory, be expanded to cover the whole economic system, in practice, several generalisations have to be made. Therefore, it is very important to openly state the data sources and the generalisations made and analyse the uncertainties of the study through a sensitivity analysis, for example (see Huijbregts, 2001 for a discussion on how to treat the uncertainties in LCA). One further essential question when studying the sustainability performance of IS is how to make generalisations of any kind when the symbioses are all different from each other. We think that the analysis has to be made separately for each symbiosis in question, but it can be done by using a general framework, such as the one presented here.

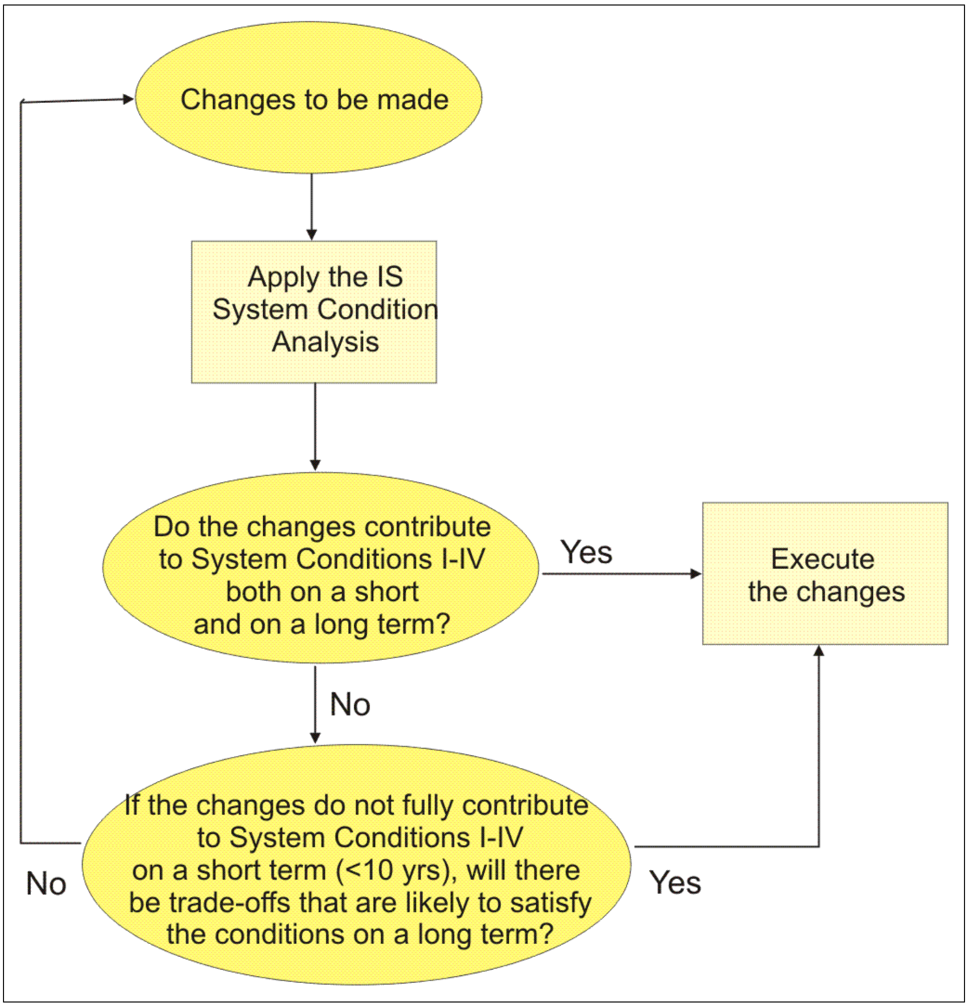
Table 2 The potential available tools and metrics for the IS system condition analysis

Spatial dimension	*System condition 1*	*System condition 2*	*System condition 3*	*System condition 4*
Local	SFA, MFA Technology assessment	RA (ecological risks) Factor X, MIPS	Qualitative assessment Hybrid LCA, LCC Factor X, MIPS EF	RA (human health risks) Factor X, MIPS SIA, SLCA
Regional	SFA, MFA	RA (ecological risks)	Qualitative assessment	RA (human health risks)
Global	LCA, Hybrid LCA, LCC Factor X, MIPS Technology assessment	LCA, Hybrid LCA, LCC Factor X, MIPS	LCA, Hybrid LCA, LCC Factor X, MIPS EF	Factor X, MIPS, SIA, SLCA

Notes: EF = Ecological Footprinting (Holmberg *et al.*, 1999; Bagliani *et al.*, 2008); Factor X (Robèrt *et al.*, 2001); Hybrid LCA = tiered, input-output based and integrated hybrid analyses (Suh and Huppes, 2005); LCC = Life Cycle Costing (Huppes *et al.*, 2004); MFA = Material Flow Analysis/Material Flow Accounting (European Commission, 2001; United Nations *et al.*, 2003); MIPS = Material Intensity Per Service Unit (Wuppertal Institute, 2007); RA = Risk Assessment (Landcare Research, 2007); SFA = Substance Flow Analysis (van der Voet, 2002); SIA = Social Impact Assessment (Becker, 2001; UNEP, 2003); SLCA = Social Life Cycle Assessment (UNEP-SETAC Life Cycle Initiative, 2006; Weidema, 2005; Dreyer *et al.*, 2006; ISO 14040, 2006, p.vi, 18).

After analysing the impacts of the system with suitable methods, the results are studied with the objective of finding out how the system should be developed in order to make it more sustainable. The temporal dimension of an IS system can then be managed by applying the procedure depicted in Figure 5 to any major changes under consideration. The procedure of Figure 5 is iterative and should be repeated until a feasible solution to the ‘problem’ (*i.e.*, the changes to be made) is achieved. The tradeoff principle in Figure 5 means that, in the short term, it may be strategically wise to accept some violation(s) of the system conditions (‘intermediate solution(s)’) if this is likely to help in moving to a sustainable path in the long term (‘permanent solution(s)’). An illustrative example here would be the gradual substitution of fossil fuels with other energy carriers (cf. discussions in Holmberg *et al.*, 1996; Holmberg and Robèrt, 2000; Robèrt *et al.*, 2002; Ny *et al.*, 2006).

Figure 5 The procedure for including the temporal dimension to IS system condition analysis (see online version for colours)



Note: This procedure should be followed whenever major changes to the system are under consideration.

4 Discussion and concluding remarks

In this article, we suggested that TNS System Conditions (Robèrt *et al.*, 2002; Ny *et al.*, 2006) could be used as guiding principles which – through a set of sustainability criteria and a series of questions derived from them (Table 1) – would crucially steer the analyses made about the overall sustainability of the IS network at hand. IE can be argued to have developed without a strategic focus. It should not be used as merely a technological concept, but also take into account wider aspects such as economic growth and the limits of technological process (Korhonen, 2004). Back casting from the basic principles of sustainability is a central feature of TNS System Conditions. The use of IE tools, such as LCA, often misses a sustainability perspective and results in complicated tradeoffs between different impacts (Ny *et al.*, 2006). When TNS System Conditions are used as a basis for setting the research questions or deciding how to develop a system, expensive investments in unsustainable technologies or practices that are not necessary from the sustainability perspective can be avoided. Even more importantly, critical points from the perspective of sustainability, which might otherwise go unnoticed when only focusing on the present situation, can be identified (Ny *et al.*, 2006; Byggeth *et al.*, 2007).

TNS has three strategic criteria, *i.e.*, direction towards the overall vision of TNS principles, flexible platforms (avoidance of blind alleys or dead ends) and a sufficient economic, social and environmental return on investments to fuel the process. The three strategic criteria have not been addressed in the article. We have left them out because in this paper, TNS principles are used as a steering framework for analysing the sustainability of IS. The overall strategic sustainable development, which is so central to TNS principles, is not addressed as such. However, we do argue that the framework suggested in this article steers the direction towards the overall sustainability vision of TNS principles. Through the guiding questions and the iterative process described in Figure 5, it does direct the development towards overall sustainability on a local level.

Flexible platforms imply that investment should always be planned so that they enable future development if more sustainable alternatives become available (*e.g.*, Korhonen, 2004). Robèrt *et al.* (2002) pointed out that each step made in the right direction should provide enough return on investment in order to keep the transition process going. Therefore, programmes of transition should combine two aspects: first, each investment should give a platform that is as flexible as possible for further investments according to the TNS framework and, secondly, each investment should give enough return on investment in order to fuel the process further. Robèrt (1999) recommended that from all flexible platforms, the most ‘low-hanging’ fruits should always be chosen, that is, the investments that are believed to yield the fastest return on investment. Good investments then yield other flexible platforms. This process is repeated iteratively.

Since these aspects have been left out of the scope of this paper, the authors wish to emphasise that the invaluable and very useful TNS principles are used out of their original context in the framework suggested in this paper. The limitations in the proposed approach are, therefore, by no means attributable to the principles themselves, but to the proposed approach itself.

There are (so far) few reported studies assessing the overall environmental or sustainability benefits of IS networks. At the same time, the potential tools for these kinds of analyses have developed rapidly, both in number and capacity. Most of the studies conducted so far concentrate on one or a limited number of factors. They have also only used a narrow approach to the spatial system boundaries considering just the impacts taking place within the symbiosis (*e.g.*, Singh *et al.*, 2007). While it can be argued that material and energy use are central indicators for IS – as the exchange of materials and energy is a core feature of IS and very useful when identifying the opportunities to enhance cooperation among firms – they are still not enough to make statements about the sustainability of the system as a whole. Instead, we feel that an approach where the qualitative and quantitative methods are applied in parallel should be used. The qualitative and quantitative methods should not be seen as opposites (but as complements) of one another.

In the framework presented here for analysing the overall sustainability performance of IS networks, the research questions are first set on the basis of TNS System Conditions. The environmental impacts of the system are then analysed with different quantitative methods. After this, TNS System Conditions are again used when assessing how the system should be developed in order to make it more sustainable (Figure 5). Byggeth *et al.* (2007) have proposed similar sets of questions based on sustainability principles and applied them for product development. Our suggestion differs from theirs in that we plan to apply the principles for the analysis of the whole symbiosis instead of one process or product. Also, in addition to asking how the system should be developed, the emphasis here is on 'how is the system functioning at the moment?' and 'does it function more sustainably than a system where the companies are working on their own?'

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Notes

1 An IS anchor tenant (Chertow, 1998) is a key player in the network – an influential actor affecting and being affected by many other actors in the network. For example, an anchor tenant can be a Co-Production of Heat and Power (CHP) plant supplying energy to the industry, agriculture and residential areas and utilising waste-derived biomass from all these sectors and actors in order to provide for fuels in the process.

2 The ECOREG project demonstrated the applicability of the concept of eco-efficiency at a regional scale and produced: (1) a set of indicators for measuring the conditions of regional eco-efficiency; (2) concepts, approaches, working processes and methods for constructing these indicators and (3) a mechanism for applying the indicators in monitoring changes in regional eco-efficiency and in social development (Seppälä *et al*., 2005; Mickwitz *et al.*, 2006; Rosenström *et al.*, 2006; Toikka, 2005).

3 Human needs are to be met worldwide and they refer to the basic needs for sustaining life, but also to all needs for maintaining health – including emotional and social needs (Robèrt *et al*., 2002, p.199).

4 The impact categories recommended by the international LCA community will be the point of departure (UNEP-SETAC Life Cycle Initiative: http://lcinitiative.unep.fr/, 14 May 2008).

PAPER II

Industrial symbiosis contributing to more sustainable energy use

An example from the forest industry in Kymenlaakso, Finland

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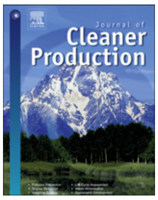

Industrial symbiosis contributing to more sustainable energy use – an example from the forest industry in Kymenlaakso, Finland

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A B S T R A C T

Industrial symbiosis (IS) studies the physical flows of materials and energy in local industrial systems using a systems approach. In this study the total fuel and energy use, and greenhouse gas emissions are calculated for an 'industrial park' operating in the same manner as an IS. Moreover the relevance of industrial symbiosis, particularly one centred on pulp and paper manufacturing, in moving towards more sustainable fuel consumption and reduced greenhouse gas emissions is discussed. The system is compared to hypothetical stand-alone production. Moreover, possibilities to reduce the energy use and total greenhouse gas emissions of the park are identified.

1. Introduction

1.1. Industrial symbiosis, energy use and climate change

Industrial symbiosis (IS), a key concept of industrial ecology [1,2], studies the physical flows of materials and energy in local industrial systems using a systems approach (e.g. [3,4]). A central idea of the concept is that companies and other economic actors form networks of suppliers and consumers, which bear a resemblance to natural ecosystems. In order to survive and maintain their productivity, these actors rely on resources available in the natural environment. Thus, the industrial symbiosis approach takes a different perspective on society than traditional organizational, social or economic studies do. Instead it studies economic systems through their material and energy flows [5]. In an ideal IS, waste material and energy are utilised between/among the actors of the system and the consumption of virgin raw material and energy inputs as well as the generation of wastes and emissions are thereby, reduced [3]. An IS can also include the exchanging of information or services, such as logistics, training and system planning [6]. Industrial symbioses systems are sometimes also called eco-industrial parks (EIPs) (e.g. [7]).

Climate change has become a more and more important topic during recent years. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) further confirms the anthropogenic impact on global warming [8]. Energy related issues and the reduction of greenhouse gas (GHG) emissions are being given an increasing dominance in environmental policy both nationally and internationally. The EU has committed itself to reducing its GHG emissions by 20% by the year 2020 (1990 as a base year), a target that will be challenging to achieve [9]. The U.S. has until recently been reluctant to commit itself to any binding emission targets unless developing countries are also involved. Lately, however, the U.S. government has taken a more positive attitude towards requisite emission targets [10]. President Barrack Obama has declared his ambitions to work to fulfil his campaign promise of reducing CO_2 emissions by 80% by 2050 [11]. In 2007 parties to the UN Framework Convention on Climate Change agreed to form an ambitious and effective response to climate change to be finalised at the end of 2009 in Copenhagen. The year 2009 is therefore, an important year in the international efforts to address climate change, culminating in the United Nations Climate Change Conference in Copenhagen, 7–18 December, where industrial countries are expected to agree to cut their emissions by 20–40% by 2020 (e.g. [12]). Since GHG emissions are considered a primary environmental concern, and energy use of industrial companies is often the principal source of these emissions, energy use and GHG emissions arguably present a good proxy for the analysis of environmental impacts ([13,14] for discussion see also [15]).

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1.2. Previous studies

Although many qualitative descriptions of industrial symbioses have been published, there is a lack of quantitative tools for the assessment of their sustainability (e.g. [4,16], for a review of previous studies, see [17]). Existing studies that deal with the environmental performance of IS have mainly concentrated on the materials and energy flows as well as the associated emissions taking place within the IS itself (see e.g. [18–22]). The upstream or downstream materials and energy flows or emissions have usually been excluded.

Some authors have concentrated specifically, on the energy use of industrial symbioses or EIPs. For example, Fichtner et al. [13], studied the economic and environmental benefits of the energy exchanges of an industrial company network in Germany. The network consisted of six companies situated near the Rhine harbor of Karlsruhe. All the companies were key actors in the energy sector of Karlsruhe. The results indicated that the installation of a combined cycle power plant would be the best option in terms of sustainability. It was found that the contribution to global warming of the actors in the park could be reduced by ca. 21%.

Beyene [23] presented the concept of an energy park and argued that improvements in energy usage could be taken as the primary objective of industrial ecosystem development. In the proposed model, the eco-industrial park would be optimized for its energy use. This way the potential benefits of combined heat and power (CHP) production could be more fully exploited while the weaknesses (such as the varying energy demands of individual plants) could be minimized.

In their study on the evolution of the Finnish Uimaharju forest industry park, Korhonen and Snäkin [24] quantified the carbon dioxide emissions from the fossil fuel use of the park in 1991 and 2000. In addition, they analysed the potential emission savings achieved through the supply of surplus electricity to the national grid. The results showed that substantial potential savings could be achieved through the symbiosis, particularly if the surplus electricity was assumed to replace coal and not average electricity.

Wolf and Karlsson [25] compared different tools for environmental systems analysis and for energy systems analysis and considered their applicability to industrial symbiosis. As a case study they used a hypothetical forest industry system. The system's CO_2 emissions were studied with an optimisation method based on mixed integer linear programming and compared to emissions from stand-alone plants. The results indicated that the emissions can be smaller from an IS than from a system consisting of stand-alone plants.

1.3. Scope of the paper

Over 60% of the Finnish land area is covered by forests and the forest industry has traditionally been a very important sector in Finland. In 2005 approximately 16% of the total industrial value added originated from pulp and paper production and approximately 4% from the manufacture of wood products [26]. Most of the products were exported: the share of exports in paper and paperboard production was about 90% in 2005 [27]. Pulp and paper production and manufacture of wood products together constituted approximately 20% of the total exports of Finland. The most important destination countries were Germany and the UK [27]. The Forest industry is concentrated in certain areas of Finland. In the South-Eastern Kymenlaakso region where our case study is located, the share of pulp and paper production of the total value added was the highest, ca. 20% [27].

Pulp and paper production is a large consumer of energy, particularly electricity. In 2005 it used over 25% of the total electricity consumption in Finland [27]. However, due to the large use of renewable fuels, the fossil GHG emissions of the sector were less than 10% of the total Finnish emissions [27,28]. Altogether wood-based fuels constitute ca. 20% of the total energy use in Finland [28].

'Symbiotic' operation is very typical of the Scandinavian forest industry and it has been studied in several case studies (e.g. [4,25,29,30]). Pulp and paper production units usually form local industrial systems, which in addition to the pulp and/or paper plants, consist of e.g. a power plant, chemical manufacturing plants, waste management facilities and sewage treatment plants. Often a local town is involved in the system as well through district heat and electricity supply from the power plant [30].

In this paper, the 2005 fuel use and GHG emissions of an industrial area, operating in the same manner as an IS, are analysed using a life-cycle approach. In addition to the direct fuel use and emissions, also fuel use and emissions resulting from raw material production, fuel production and main waste management processes are included. Moreover, most of the transportation are taken into account. The system is compared to a hypothetical stand-alone system. In addition, potential improvements in the environmental performance of the system are discussed. Moreover, the relevance of an IS, particularly one centred around pulp and paper manufacturing, in moving towards more sustainable fuel consumption and reduced GHG emissions is analysed.

2. Materials and methods

2.1. Case-study system – Kymi EIP

The case-study system was developed around an integrated pulp and paper manufacturer, the Kymi plant of the UPM Kymmene Corporation (hereafter to be referred to as the Kymi EIP, Fig. 1, see also [17]). Other actors of the park include three chemical plants, a power plant, a water purification plant, a sewage plant and a landfill. The park also has close interactions with a regional energy supplier, a communal sewage plant and local agricultural production.

The pulp and paper plant mainly uses black liquor in its own energy production. In addition, it delivers bark, wood chips, fibre suspension and milled peat to the power plant of the park to be used as a fuel. The power plant then delivers steam, electricity and heat to the pulp and paper plant, which in turn sells electricity and heat to the chemical factories. In addition, the power plant produces electricity and heat for a local energy distributor. Thus, in addition to the park, the wood-based residues generated in the pulp and paper plant have an important influence on the energy supply of the whole community. All the actors of the Kymi EIP, except the hydrogen peroxide plant, rely partly or completely on the park, i.e. the power plant and the pulp and paper plant, in their energy consumption. The hydrogen peroxide plant produces part of its heat and electricity itself and purchases the rest from the markets.

2.2. Calculation tools and data

The GHG emissions and fuel use of the system were calculated by applying the life-cycle inventory (LCI) methodology of life-cycle assessment (LCA). The inventory was conducted according to the EN ISO Standard 14040:2006 and 14044:2006. The product system includes the production of raw materials, fuels and electricity used by the symbiosis actors, as well as transportation and management or recycling of the main waste materials (Fig. 1).

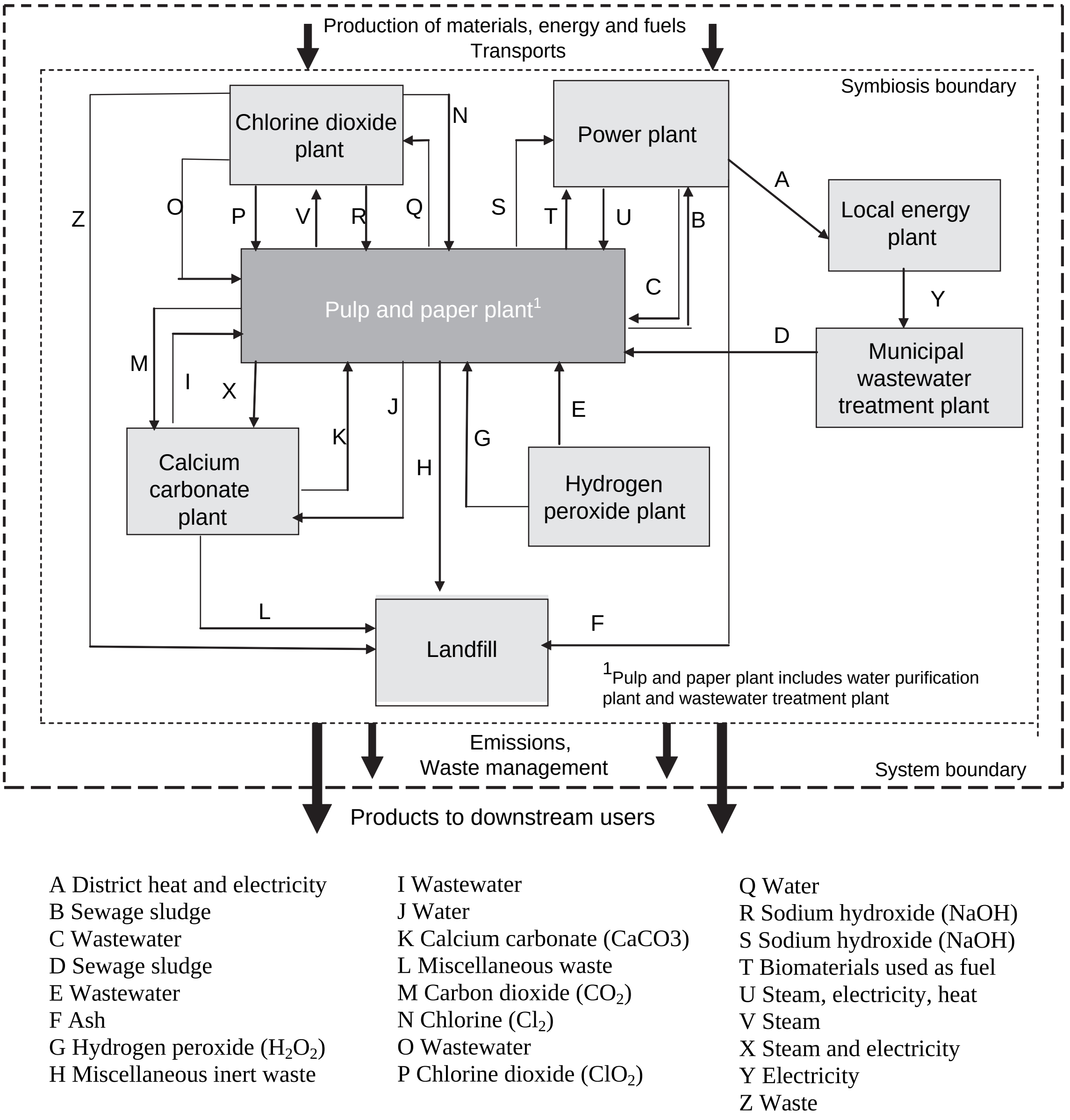

Fig. 1. Processes included in the Kymi Eco-Industrial Park (Kymi EIP). The outer dashed line represents the system boundary of the study and the inner line the boundary of the symbiosis. The total system includes fuel use and emissions from raw material, fuel and energy production processes and transportation. Fuel use and emissions from the disposal and recovery of the main waste materials have also been included. Processes included within the symbiosis consist of direct fuel use of the symbiosis actors and direct emissions occurring at the site. The functional unit of the study is one year production (tonnes in 2005) of the whole symbiosis at the gate of the park. A District heat and electricity; B Sewage sludge; C Wastewater; D Sewage sludge; E Wastewater; F Ash; G Hydrogen peroxide (H_2O_2); H Miscellaneous inert waste; I Wastewater; J Water; K Calcium carbonate ($CaCO_3$); L Miscellaneous waste; M Carbon dioxide (CO_2); N Chlorine (Cl_2); O Wastewater; P Chlorine dioxide (ClO_2); Q Water; R Sodium hydroxide (NaOH); S Sodium hydroxide (NaOH); T Biomaterials used as fuel; U Steam, electricity, heat; V Steam; X Steam and electricity; Y Electricity; Z Waste.

Data on the direct raw material and energy use, emissions and waste production were received from the companies themselves, from their environmental permits and from the VAHTI database of the Finnish Environmental Administration.[1] Data on the production of raw materials, recycling and the treatment of waste were taken from available LCA databases (mainly the Ecoinvent database[2]) [31], the VAHTI database [32], companies' environmental reports and literature (Appendix 1). The calculations were conducted using the KCL-ECO LCA software [33].[3]

2.3. Comparison to a stand-alone system

The GHG emissions of the Kymi EIP system were compared to two hypothetical stand-alone systems in which the actors of the system would be working in isolation. The stand-alone systems

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[1] The VAHTI database is an emissions control and monitoring database of the Finnish Environmental Administration.

[2] Ecoinvent: www.ecoinvent.ch.

[3] KCL-ECO: www.kcl.fi/page.php?page_id=166.

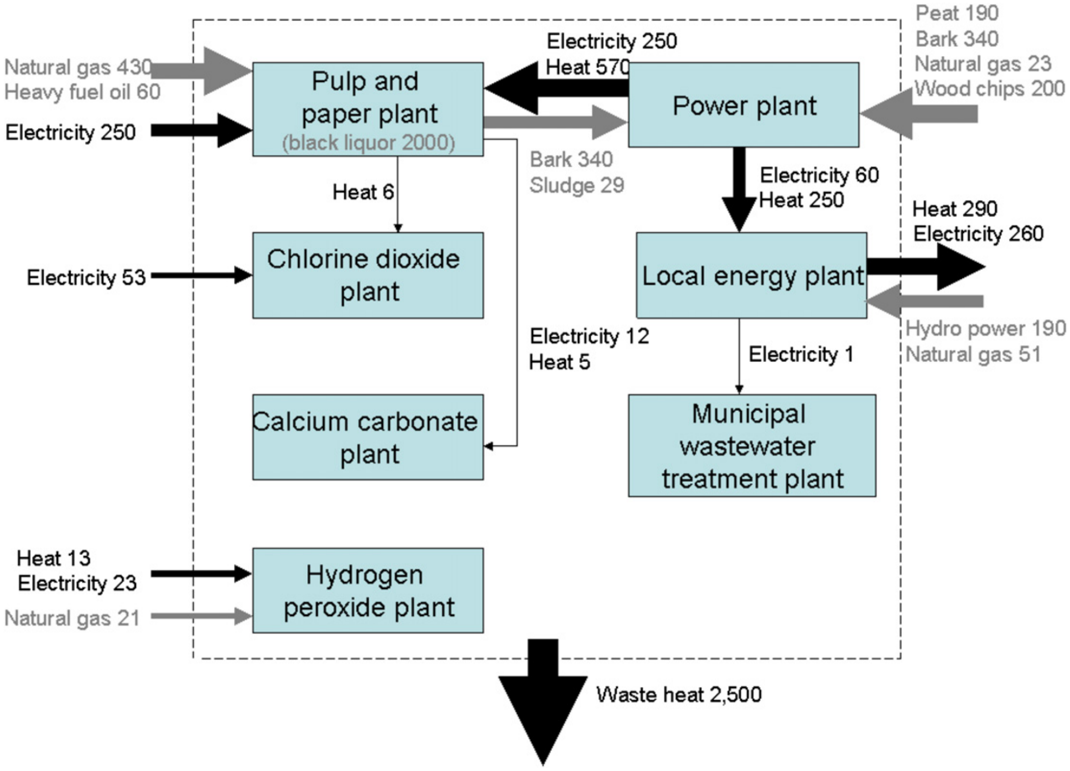

Fig. 2. Direct inputs and outputs (GWh) of fuel, electricity and heat to and from the Kymi EIP in 2005. The grey lines represent fuel flows and the black lines heat and electricity flows. The thickness of the arrow reflects the magnitude of the flow. (Black liquor consumption of the pulp and paper plant is shown in brackets.)

were designed under the assumption that they represent possible alternative states for the Kymi EIP. However, it should be emphasised that these systems are hypothetical and do not exist anywhere as such. Nor do they represent likely future developments of the Kymi EIP.

In *Case 1*, the pulp and paper plant would not receive electricity or heat from the power plant but would purchase them from the markets. The calcium carbonate ($CaCO_3$) plant and the chlorine dioxide (ClO_2) plant, which presently obtain electricity and steam from the pulp and paper plant, would also purchase energy from the markets. In addition, it is assumed that the power plant would not receive any wood from the pulp and paper plant. Instead it would increase its peat consumption and buy wood residues from the markets.[4] It would produce heat and electricity for the markets and negative emissions are thus calculated for that production. Data for the power plant's heat and electricity production were taken from E.ON Finland Oyj's Joensuu plant, which is a similar sized CHP plant using 45% peat and mainly wood residues as well as a small amount of landfill gas and heavy fuel oil in its energy production. In addition, the calcium carbonate plant would not obtain CO_2 from the pulp and paper plant but would buy liquid CO_2 instead.[5] Data on the Joensuu plant were received from the plant's environmental permits and the VAHTI database [32,35]. Allocation for heat and electricity was conducted according to the benefit allocation method.[6] Heat and

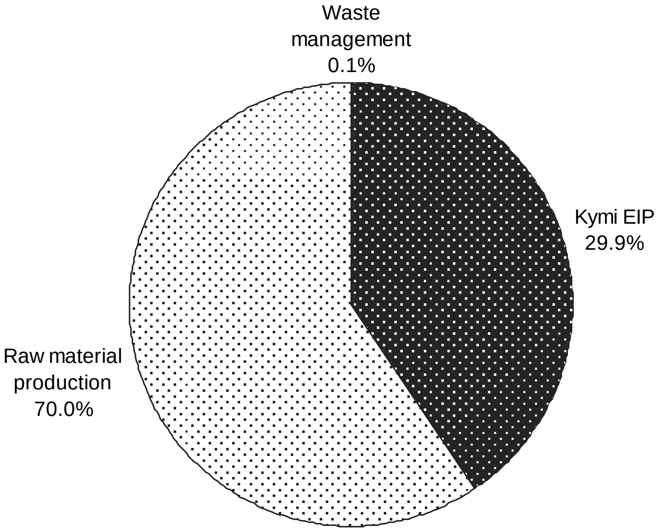

Fig. 3. The contribution of direct emissions, emissions from raw material production and waste management to the total GHG emissions caused by the Kymi EIP (% in 2005).

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[4] Approximately 6% of Finland's annual energy use is produced from peat. Peat is a renewable resource in principle, but its renewal takes several hundred years. The CO_2 emission factor for peat is 105.9 ton per TJ, i.e. approximately the same as that for lignite [34].

[5] In reality there would not be enough liquid CO_2 available to replace the CO_2 obtained from flue gas (Taskinen, I., UPM Kymmene, personal communication, October 17, 2008).

[6] In the benefit allocation method, emissions of combined heat and power (CHP) production are allocated in relation to the alternative fuel consumption ratios (see e.g. [36]).

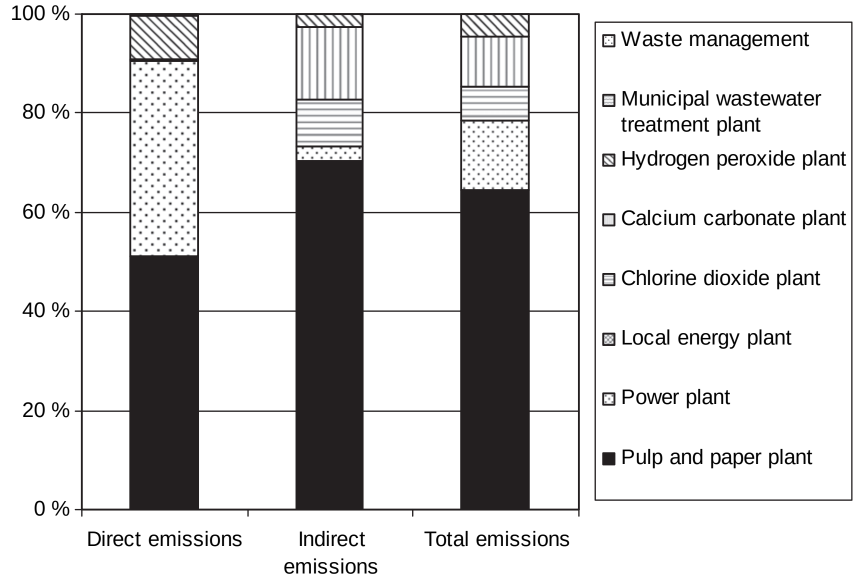

Fig. 4. The contribution (%) of different actors to the direct, indirect and total GHG emissions of the Kymi EIP system in 2005. The shares of waste management, municipal wastewater treatment plant and local energy plant were less than 1%.

electricity production of the power plant were assumed to replace Finnish average electricity and heat production (for data sources see Appendix 1).

In *Case 2*, everything else remains the same as in Case 1 but the power plant would solely use peat in its energy production. Data on the power plant in this case were taken from Myllymaa et al. [37]. Data sources for peat production, wood residue production, Finnish average electricity and heat production and liquid carbon dioxide production were the same as in the base case (Section 2.2). As in Case 1, allocation for heat and electricity was conducted according to the benefit allocation method.

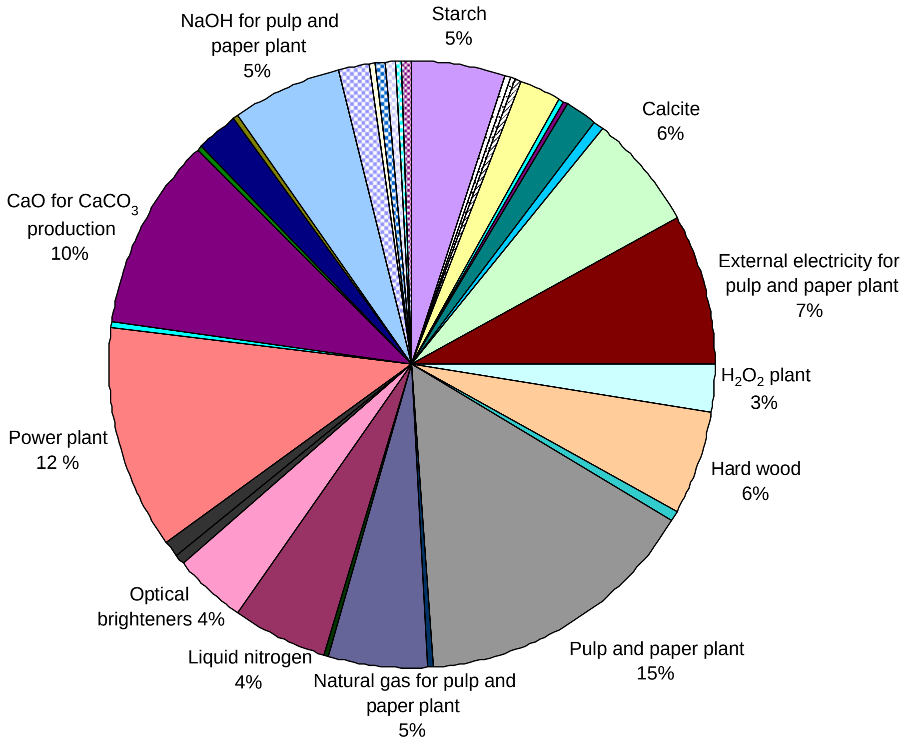

Fig. 5. The main processes contributing to the total GHG emissions of the Kymi EIP system in 2005. Altogether the system includes almost 70 processes.

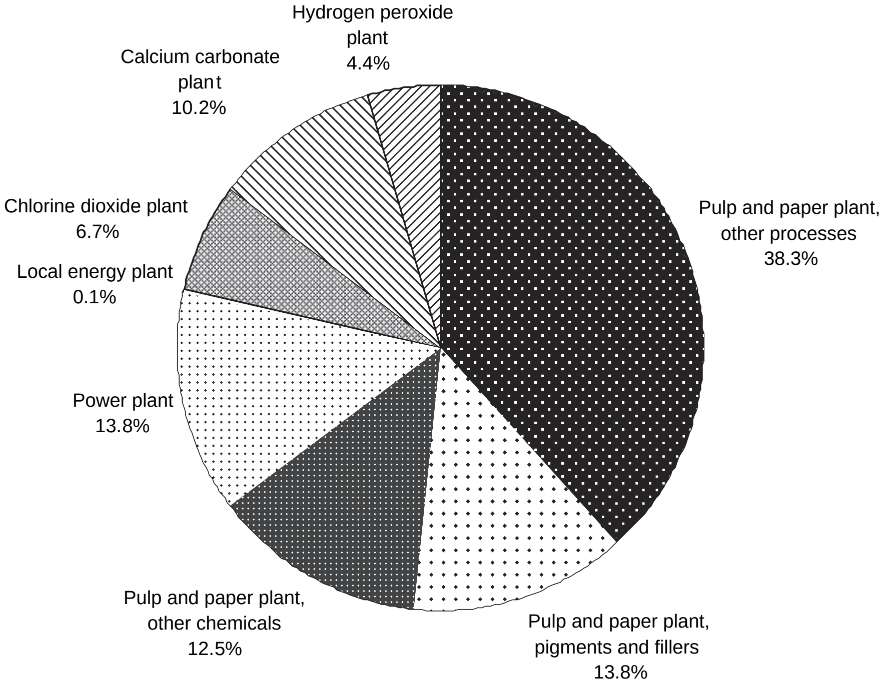

Fig. 6. The share of pigments and fillers (starch, calcite, talc and kaolin) and other chemicals of the total GHG emissions (in CO_2 eqv.) of the system in 2005. The shares of waste management, municipal wastewater treatment plant and local energy plant were less than 1% and are therefore, not shown in the figure.

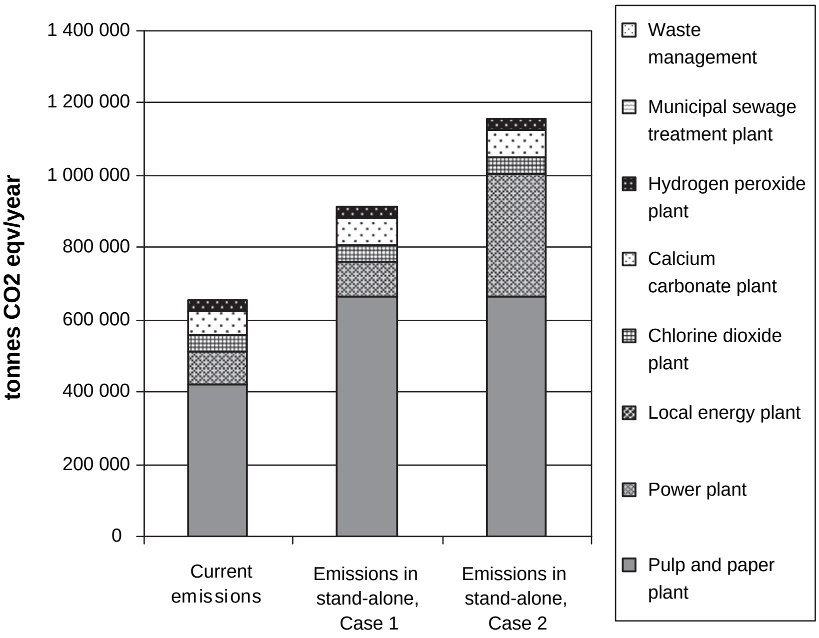

Fig. 7. Current emissions compared to a situation where the actors would operate on in isolation. Case 1: the power plant is replaced by a CHP plant that uses both peat and wood (ca. 45–55% ratio); Case 2: the power plant is replaced by a CHP plant, which uses only peat.

3. Results

3.1. Flows of energy in the Kymi EIP

The Kymi EIP mainly uses wood and natural gas in its energy production, 540 GWh and 525 GWh respectively in 2005. All of the wood was consumed by the power plant (Fig. 2). However, it should be emphasised that the pulp and paper plant uses almost 2000 GWh of black liquor in its energy production. In addition, it uses 43 GWh of odorous gases from pulp production for energy generation. Most of the natural gas was consumed by the pulp and paper plant as well. The use of peat amounted to 190 GWh and that of hydropower 190 GWh. The consumption of heavy fuel oil was 60 GWh; it was all used by the pulp and paper plant. The park purchased 326 GWh electricity and 13 GWh from outside the park in 2005. The amount of heat released into the wastewater was 2500 GWh. As the temperature of the waste heat is so low it is not profitable to utilize it in district heating. Moreover the demand for additional heat either in housing or in process industry is low in the area.

3.2. Greenhouse gas emissions

The total fossil GHG emissions of the system (including emissions from raw material production and transportation) amounted to 653,000 ton CO_2 eqv. in 2005. The direct emissions caused by the actors of the Kymi EIP were 196,000 ton CO_2 eqv., i.e. 30% of the total (Fig. 3). Approximately 70% of the total emissions were caused by the production of raw materials (including transportation of the raw materials). The contribution of waste management processes to the total emissions was negligible.

The power plant caused approximately 40% of the direct emissions of the system (Fig. 4). However, its contribution to the indirect emissions was less than 3%. This is due to the power plant's low requirement of fossil fuels and auxiliary raw materials. The pulp and paper plant produced ca. 50% of the direct emissions and 70% of the indirect emissions.

The direct emissions of the pulp and paper plant constituted approximately 15% and those of the power plant 12% of the total emissions of the system (Fig. 5). Other main contributors were calcium oxide (CaO) production, externally produced electricity for pulp and paper plant, calcite, natural gas and sodium hydroxide production.

Pigments, fillers and other chemicals used at the pulp and paper plant had a large impact on the total emissions of the system (Fig. 6). Altogether, over 35% of the total emissions were caused by their production. Since many of the pigments and fillers are transported over fairly large distances transportation made up approximately 11% of the total emissions related to their production.

3.3. Comparison to a stand-alone system

The GHG emissions of the Kymi EIP were compared to two hypothetical stand-alone systems in which the actors of the system would be operating in isolation (see Section 2.3). Both cases resulted in increased CO_2 emissions (Fig. 7). In Case 1, emissions increased by ca. 40% and in Case 2 by ca. 75%. In both cases the emissions of the pulp and paper plant grew by 240,000 ton. In Case 1 emissions of the power plant increased by ca. 10% and in Case 2 they almost tripled due to the high emissions from peat generated energy.

4. Discussion

In this study the total fuel use and GHG emissions of an eco-industrial park, developed around a pulp and paper plant, were calculated. The results show that most of the GHG emissions caused by the system (ca. 2/3) result from raw material production outside the system. This share is perhaps, surprisingly large and reveals that the Scandinavian pulp and paper production, albeit relying largely on renewable fuels is not as carbon neutral as it is often considered (e.g. [38]). This finding also highlights the problems of current greenhouse gas quotas, which only consider emissions occurring within national borders (for a discussion on GHG emissions embodied in trade and consumptions-based GHG-quotas see [39,40]) On the other hand it must be emphasised that pulp and paper production in Finland is very export-oriented and most of the produce is exported. The pulp and paper plant and the power plant are key actors of the symbiosis, which is reflected in their large contribution to the total GHG emissions as well.

There are several resource and energy exchange relationships between/among the actors of the park, which reduce their dependence on the outside world and thereby, reduce their collective greenhouse gas emissions. Presently most of the fuels used by the system are wood-based. As shown in Section 3.3 the emissions of the system would be increased by 40–75% if the current material and energy exchange links did not exist. Further reductions could be achieved, for example, by using wood ash (produced by the power plant) as a fertiliser and thereby, replacing inorganic fertilisers. Moreover, replacing peat with wood at the power plant would also reduce CO_2 emissions. Another minor reduction could be achieved if the calcium carbonate plant received all the carbon dioxide from the pulp and paper plant rather than using liquid CO_2.

In summation, the results reveal that an EIP or an IS can reduce GHG emissions compared to a system where the actors are operating on their own. However, as Cases 1 and 2 show, assumptions on how the energy is produced in the stand-alone situation significantly, impact the results. In addition, it should be pointed out that most of the emission reductions in this case originated from changes in the operation of the power plant. However, if other environmental interventions were included in the study, also other processes, such as the nutrient replacing sewage sludge addition from the municipal wastewater treatment plant, replacing nutrients, might have had a larger impact on the results as well.

The case study of this article was based on pulp and paper production where energy production was largely based on wood-based fuels. The results might be different if the case study had been from another industry, which is more dependent on fossil fuels. For example, Chertow and Lombardini [22] studied an IS system in which a coal-fired power plant utilises process water from nearby sources thereby, avoiding freshwater withdrawals and sells steam to an oil refinery plant and thus decreases the refinery's emissions. Chertow and Lombardini calculated that although the arrangement leads to considerable reductions in SO_2, NO_x and PM_{10} emissions it simultaneously increases CO_2 and CO emissions due to switching from oil to coal.

The forest industry is currently undergoing major structural changes in Finland. Operating costs have been increasing for several years and the profitability of the sector has decreased. An additional challenge is posed by the increased tariffs on timber that Russia (an important source for wood in Finland) is planning to set. New solutions are needed in order to secure the future of the sector. Some have proposed a type of bio-refinery in which pulp mills would gasify biomass materials to create synthesis gas and then transform this syngas into different green fuels and chemical feed-stocks [41]. Sassner and Zacchi [42] have suggested that wood-based energy production could be integrated with bioethanol production. The carbohydrate fraction of the wood residues could first be converted to ethanol and the solid residue would then serve as a solid fuel. Thus, production of new innovative products within a symbiotic arrangement could reduce the environmental burden and simultaneously secure production and local employment, which could provide the economic–environmental–social win–win–win results mentioned by Gibbs and Deutz [43] and Korhonen [2].

The integration of pellet production to a forest industry system has been studied in Sweden by Wolf et al. [44] and Andersson et al. [45]. Finland has committed itself to increasing its share of renewable fuels to 38% of the final energy consumption by 2020 [46]. The recently published Finnish long-term climate and energy strategy encourages increased use of pellets in industry and housing [47]. The Kymi EIP annually produces approximately 2500 GWh of waste heat, which is released into water. The most energy-demanding process in pellet production is usually the drying process (see e.g. [45]). According to Andersson et al. [45], a flue gas dryer typically requires circa 0.8 MWh per 1 ton of pellets produced. Assuming that 50% of the waste heat from the Kymi EIP could be recovered and used for drying in integrated pellet production, approximately 6900 GWh pellets could be produced. However, currently there is no excess saw dust or bark available in the park so it would need to be transported to the site.

The research method of this study was life-cycle inventory (LCI) taking into account only greenhouse gas emissions and fuel consumption. A more complete insight into the overall environmental impacts of the IS could be attained by extending the analysis to other environmental impacts as well. In addition, the study method used was a traditional LCA, which results in upstream and downstream cut-offs. In recent years, LCA has been linked to environmental input-output accounting in order to avoid these cut-offs. These so-called hybrid methods have been reviewed by e.g. Suh and Huppes [48]. Since the purpose of this study was to analyse the role of IS in reducing greenhouse gas emissions and to look at the role of raw material production processes in relation to processes within the symbiosis, applying a full-scale integrated LCA was not considered necessary.

5. Concluding remarks

Total GHG emissions of the system amounted to 653,000 ton CO_2 eqv. in 2005. Most of them, ca. 2/3, resulted from raw material production. The contribution of waste management and recycling processes was minor. Altogether, over 35% of the total emissions were caused by the production of pigments, fillers and chemicals. Since many of the pigments and fillers are transported over fairly large distances, transportation made up approximately 11% of the total emissions related to their production. The large impact of upstream processes on total GHG emissions shows that the system under study is very interdependent upon the surrounding environment. Studying an IS on its own, isolated from the surrounding environment may therefore, yield a very different picture of its environmental impacts than when upstream processes are included in the study as well. Thus, upstream production processes and their environmental impacts should be taken into account when making recommendations on how to develop a particular IS or EIP. These findings imply that Finnish pulp and paper production is not as carbon neutral as has sometimes been stated. Nevertheless, comparisons with a system where the actors would be operating in isolation, indicates that an IS can provide environmental benefits. It should be emphasised, though, that the case IS in this study was based on pulp and paper production, and it mainly uses renewable fuels in energy production. Had the case study been based on fossil fuels the results might have been different.

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Appendix 1. References used for the raw materials (see also [62]).

	Process	Source
Pulp and paper plant	Polyaluminium chloride	[49]
	CO_2, liquid	[32,50]
	Latex	[32,51]
	Talc	[32,52]
	Starch	[31,53]
	$CaCO_3$	[32,54]
	Calcite	[32,55]
	Other chemicals	[31]
	Fuels	[31]
	Sulfate pulp	[56]
	Other raw materials	[31]
	Heat, average Finnish production	Koskela, S., Finnish Environment Institute, personal communication
	Electricity, average Finnish	Nissinen, A., personal communication
Power plant	NaCl	[33]
	Other chemicals	[31]
	Natural gas	[31]
	Peat production	[32,57,58]
	Wood chips and bark	[31]
Chlorine dioxide plant	Chemicals	[31]
	Electricity, average Finnish production	See pulp and paper plant
Hydrogen peroxide plant	Natural gas	[31]
	Electricity, average Finnish production	See pulp and paper plant
	Heat, average Finnish production	See pulp and paper plant
Calcium carbonate plant	Chemicals	[31]
	Electricity, average Finnish production	See pulp and paper plant
	Polyaluminium chloride	[49]
	Ferric sulfate	[59]
	Natural gas power plant	[32,60]
	Hydropower, average Finnish production	[31]
	Natural gas production	[31]
	Electric train	Average Finnish electricity production; Nissinen (2007) and [61]
	Diesel train	[31,61]
	Timber truck	[31,61]
	Full trailer combination truck	[31,61]
	Roll-on ship	[31,61]

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PAPER III

Analyzing the Environmental Benefits of an Industrial Symbiosis

Life Cycle Assessment (LCA) Applied to a Finnish Forest Industry Complex

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Analyzing the Environmental Benefits of Industrial Symbiosis

Life Cycle Assessment Applied to a Finnish Forest Industry Complex

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Keywords:
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Supporting information is available on the *JIE* Web site

Summary

Studies of industrial symbiosis (IS) focus on the physical flows of materials and energy in local industrial systems. In an ideal IS, waste material and energy are shared or exchanged among the actors of the system, thereby reducing the consumption of virgin material and energy inputs, and likewise the generation of waste and emissions. In this study, the environmental impacts of an industrial ecosystem centered around a pulp and paper mill and operating as an IS are analyzed using life cycle assessment (LCA). The system is compared with two hypothetical reference systems in which the actors would operate in isolation. Moreover, the system is analyzed further in order to identify possibilities for additional links between the actors. The results show that of the total life cycle impacts of the system, upstream processes made the greatest overall contribution to the results. Comparison with stand-alone production shows that in the case studied, the industrial symbiosis results in modest improvements, 5% to 20% in most impact categories, in the overall environmental impacts of the system. Most of the benefits occur upstream through heat and electricity production for the local town. All in all it is recommended that when the environmental impacts of industrial symbiosis are assessed, the impacts occurring upstream should also be studied, not only the impacts within the ecosystem.

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Introduction

Industrial symbiosis (IS) studies examine the flows of materials and energy in local industrial systems using a systems approach (Chertow 2000; Wolf 2007; Zhao et al. 2008).[1] The approach analyzes economic systems through their material and energy flows (Hart et al. 2005). The key idea of the concept is that in an IS, waste material and energy is shared or exchanged among the actors of the system and the consumption of virgin material, energy inputs, and the generation of waste and emissions are thereby reduced (Korhonen and Snäkin 2003; Ulgiati et al. 2007). Literature on identified industrial symbioses, industrial ecosystems (IES), and eco-industrial parks has burgeoned during the past 10 to 15 years (cf. Sterr and Ott 2004). While numerous descriptive analyses have been conducted on the concept, there are relatively few quantitative assessments of the environmental benefits of industrial symbioses (for a discussion and review, see Sokka et al. 2008 and 2009).

Most of the assessments of the environmental impacts of industrial symbioses have focused on the ecosystem itself and excluded upstream and downstream impacts. For instance, the economic and environmental costs and advantages of symbiosis partners were assessed in Guayama, a symbiosis network in Puerto Rico (Chertow and Lombardi 2005). According to the study, the symbiosis resulted in a substantial decrease in some emissions, such as SO_2, and in water extraction, but simultaneously there was an increase in the emissions of CO_2. The researchers concluded that the participating organizations derived considerable economic and environmental benefits from the symbiosis but that those benefits were unevenly distributed among the participants.

In another example, Van Berkel and colleagues (2009) quantitatively assessed 14 industrial symbioses in Kawasaki, Japan. They found that the by-product exchanges of the symbioses altogether diverted 565,000 tons of waste from waste management annually. In addition, it was estimated that the documented resource exchanges compensated for 513,000 tons of raw material use annually. However, the researchers pointed out that there are trade-offs between material flow benefits and other environmental impacts. They called for further research to develop comprehensive methods for the quantification of the environmental and economic benefits of industrial symbioses.

Singh and colleagues (2007) studied an agrochemical complex consisting of 13 chemical and petrochemical industries in the state of Mississippi, USA. They conducted a so-called "entry to exit" life cycle assessment (LCA) study of the system, thus considering only materials used inside the complex. Raw material production and waste treatment were not taken into account. The environmental impacts of the system were analyzed using life cycle impact assessment (LCIA). The researchers concluded that LCA is an extremely useful tool for analyzing and comparing different designs of industrial ecosystems and recommended conducting a comprehensive LCA before starting a new eco-industrial park in order to assess the potential advantages and disadvantages of the system and to thereby select the best design option from the perspective of sustainable development.

Only a few studies have also considered the life cycle impacts of industrial symbioses. Sendra and colleagues (2007) applied material flow analysis (MFA) methodology to an industrial area in Spain. In the study, MFA-based indicators, with additional water and energy indicators, were used to evaluate how the area could be transformed into an eco-industrial park. The study thus had a life cycle view but did not include an impact assessment. More recently, Eckelman and Chertow (2009) studied industrial waste production in Pennsylvania. They combined waste data from the area with life cycle inventory (LCI) data and thereby calculated the present and potential environmental benefits of utilizing this waste. It was found that in all cases except for the energy use of waste oil and substitution of virgin steel with scrap steel, the reuse of the waste streams studied results in positive environmental impacts compared with the use of the substituted material.

Uihlein and Schebek (2009) compared the environmental impacts of a ligno-cellulosic feedstock biorefinery to the production of fossil alternatives using LCA. The system was not considered a form of industrial symbiosis, but in practice its operation is similar. Since the ligno-cellulosic feedstock biorefinery has not yet been implemented in practice, the researchers assessed three different variants of the concept. For all variants it was found that the environmental performance of the biorefinery was superior to the corresponding fossil-based production in some impact categories and inferior in other impact categories. Nevertheless, from the overall results the researchers concluded that from an environmental point of view, the ligno-cellulose biorefinery concept would be beneficial compared with the existing fossil production options.

In another study on the symbiotic exchanges within an eco-industrial park in China, it was suggested that companies tend to out-source the lowest value-added and often pollution-intensive production of materials and intermediate components to outside the parks (Shi et al. 2010). Therefore, the researchers concluded that in the long-run assessments of the environmental performance of eco-industrial parks should be extended to these spill-over effects as well.

In our previous study (Sokka et al. 2009), we focused on the CO_2 emissions and fuel consumption of the same IES as in this study. It was found that upstream processes accounted for over two thirds of the total fossil greenhouse gas (GHG) emissions of the system. Production of pigments and fillers had a considerable impact on the total results, causing altogether over 35% of the total fossil GHG emissions. However, in order to give an overall picture of the environmental performance of the case system, it is important to look at other environmental impacts as well, since GHG emissions alone do not give a complete picture of the environmental performance of the system.

In this study, the environmental impacts of an industrial symbiosis that developed around pulp and paper production are assessed with LCA and compared with two hypothetical reference systems in which the actors work on their own. Moreover, the possibilities for additional linkages between the system's actors are studied in order to assess their environmental relevance. Yet, instead of providing a full, detailed assessment of the system's environmental impacts, the main objective of this study is to analyze the potential relative environmental benefits achieved through an industrial symbiosis and to discuss the conditions under which these benefits may be achieved.

Materials and Methods

Case Study IES

The chosen case study IES is situated in the town of Kouvola in southeastern Finland. The system has evolved spontaneously (meaning that it was not intentionally developed as an industrial symbiosis) around an integrated pulp and paper manufacturer, the Kymi mill of the UPM Kymmene Corporation (figure 1). Paper production began at the site in 1874. The current annual production capacity of the integrated facility is 840,000 tons of paper and 530,000 tons of pulp. Some 55% of the wood used by the UPM Kymi mill is hardwood (birch) and the rest softwood (pine and spruce). The mill produces higher-quality papers (coated and uncoated fine papers), which typically contain approximately 20% to 25% fillers (Hart et al. 2005), such as kaolin and starches. Thus, fillers and other additives are an important production input.

In addition to the pulp and paper mill, the system includes a power plant, running on wood residues and sludge from the pulp and paper mill. The power plant then sells heat and electricity back to the pulp and paper mill. The power plant also provides electricity and district heat to Kouvola town. There are three chemical plants in the system: a chlorine dioxide plant, a calcium carbonate plant, and a hydrogen peroxide plant. Besides providing chemicals for the pulp and paper mill, the chlorine dioxide and the calcium carbonate plants receive energy and chemically purified water from the pulp and paper mill. The calcium carbonate plant also utilizes carbon dioxide from the flue gases of the pulp and paper mill as a raw material. The municipal sewage plant delivers part of its sewage sludge to the wastewater treatment plant of the pulp and paper mill. The nutrient-rich sewage sludge reduces the need to add urea and phosphoric acid to the wastewater treatment process. Moreover, the pulp and paper mill manages the waste of the power plant, calcium carbonate plant, and chlorine dioxide plant.

Calculation Tools and Materials Used

The analysis was conducted with LCA based on International Organization for Standardization (ISO) standards 14040:2006 and

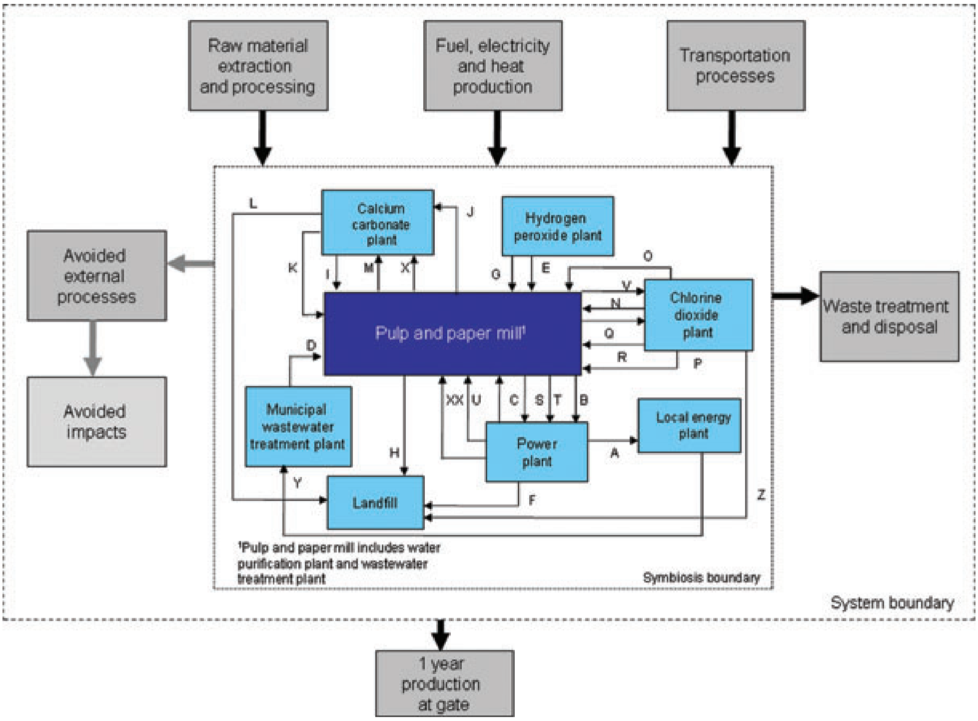

Figure 1 Processes included in the study and the flows of material and energy between the case industrial ecosystem actors. The outer line represents the system boundary of the study and the inner broken line the boundary of the ecosystem. The functional unit of the system is one year of production at the gate in 2005. A = district heat and electricity; B = sewage sludge; C = wastewater; D = sewage sludge; E = wastewater; F = ash; G = hydrogen peroxide (H_2O_2); H = miscellaneous inert waste; I = wastewater; J = water; K = calcium carbonate ($CaCO_3$); L = miscellaneous waste; M = carbon dioxide (CO_2); N = chlorine (Cl_2) wastewater; P = chlorine dioxide (ClO_2); Q = water; R = sodium hydroxide (NaOH); S = sodium hydroxide (NaOH); T = biomaterials used as fuel; U = steam, electricity, heat; V = steam; X = steam and electricity; Y = electricity; Z = waste; XX = water.

14044:2006 (ISO 2006a, 2006b). In the study, the case study IES was treated as a "black box," as one of the life cycle phases of the product system. The other life cycle phases were upstream processes, divided into the production of raw materials (including transportation) and production of energy and fuels (including transportation) used by the IES; waste management, covering the disposal and treatment of waste materials outside of the IES; and avoided impacts, which covered the inputs and outputs avoided through recycled waste (deducted from the total) (see figure 1). The functional unit of the study was the total annual production of the IES (tons or GWh in 2005) at the gate of the symbiosis.

The LCI analysis was conducted as described in our earlier article (Sokka et al. 2009). Primary data received directly from the companies and from their environmental permits and from the VAHTI database of the Finnish Environmental Administration (2008)[2] were used for the direct raw material and energy use and emissions and waste production. Secondary data received from available LCA databases, mainly the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2007),[3] from the VAHTI database (Finnish Environmental Administration 2008), other companies' environmental reports, and other literature were used for the production of raw materials and recycling and treatment of waste. The life cycle inventory assessment was conducted using the KCL-ECO LCA software (Finnish Pulp and Paper Research Institute 2004).[4] GHG emissions of the system have been discussed in another of our articles (Sokka et al. 2009) and are thus only briefly addressed here.

LCIA was conducted according to ISO standards 14040:2006 and 14044:2006. Characterization factors that are site and temporally generic have been used in many studies for reasons of practicality and due to uncertainties about the location or time at which the emissions occur (Krewitt et al. 2001; Pennington et al. 2004). However, several studies have shown that within some impact categories there may be significant variation in the estimated damage between countries due to, for example, local environmental conditions (Krewitt et al. 2001; Seppälä et al. 2006). Since most of the processes in this study took place in Finland or Russia, Finland-specific characterization factors were used for impacts on acidification, eutrophication, tropospheric ozone formation, and particulate matter (table 1). Toxicity impacts were calculated with the ReCiPe methodology (Sleeswijk et al. 2008; Goedkoop et al. 2009) and adjusted for Finland according to method described by Seppälä (2008).

In normalization, the impact category indicator results are divided by an appropriate reference value (e.g., impacts of a society's total activities in a given area over a certain time period). Since product life cycles can extend all over the world, the global system is often chosen as a reference situation (Sleeswijk et al. 2008). However, policymakers are typically interested in results on a smaller geographic scale because such results offer a more direct link to policy aims. In this study the results were normalized with European reference values (Sleeswijk et al. 2008). Weighting was not conducted as weighting is not usually recommended in comparative studies presented to the public due to its subjectivity (Pennington et al. 2004).

Hypothetical Reference Systems

Two hypothetical reference systems in which the main actors of the system work on their own were designed. It should be emphasized that these scenarios are hypothetical and their actual implications (e.g., the infrastructure required) are not assessed in this study. The reference systems were designed to contain production systems that are actually currently in use somewhere. In both of the reference systems the total energy use and the amount of products produced by the actors of the IES is the same as in the case study IES, except for the power plant, which produces less heat and electricity. However, its production is replaced by external production purchased by the town (see below).

In *Reference system 1*, the following assumptions were made:

- The local town would use electricity produced with hydropower as before, but meet the rest of its electricity demand from regular markets. Average Finnish production (Koskela and Laukka 2003) was used to represent this electricity. Instead of buying heat from the power plant, the town would use average heat from the Kymenlaakso region. The fuel profile of the district heat production in Kymenlaakso was taken from Finnish Energy Industries (2006). The power plant would only produce electricity and heat for the pulp and paper mill, and its production would be reduced accordingly. It would still utilize all the wood residues of the pulp and paper mill but purchase less wood from markets.
- The calcium carbonate ($CaCO_3$) plant and the chlorine dioxide (ClO_2) plant, which presently obtain electricity and steam from the pulp and paper mill, would also use average heat from Kymenlaakso and average Finnish electricity.
- The calcium carbonate plant would not get fossil CO_2 from the pulp and paper mill but would buy liquid CO_2 instead.[5] The CO_2 would be released in the air.
- The pulp and paper mill was assumed not to get any sewage sludge from the municipal wastewater treatment plant. Sewage sludge addition replaces urea and phosphorous acid in the wastewater treatment process of the pulp and paper mill. Therefore, extra nitrogen and phosphorus would need to be added to the system. The amount of nutrients needed was calculated with

Table 1 Impact Categories, Emissions Included in Them, and References

Impact category	*Contributing emissions*	*Source*
Climate change	Carbon dioxide (CO_2), methane (CH_4), dinitrogen monoxide (N_2O)	Solomon et al. 2007
Acidification	Nitrogen oxides (NO_X), sulphur dioxide (SO_2), ammonia (NH_3)	Seppälä et al. 2006
Aquatic eutrophication	Nitrogen oxides (NO_X), ammonia (NH_3), total phosphorous (P), total nitrogen (N)	Seppälä et al. 2004, 2006
Terrestrial eutrophication	Nitrogen oxides (NO_X), ammonia (NH_3)	Seppälä et al. 2004, 2006
Tropospheric ozone formation, impacts on human health	Methane (CH_4), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOC)	Hauschild et al. 2004
Tropospheric ozone formation, impacts on vegetation	Methane (CH_4), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOC)	Hauschild et al. 2004
Freshwater ecotoxicity, terrestrial ecotoxicity and human toxicity	Arsenic (As), cadmium (Cd), chromium (Cr), chromium IV (Cr IV, water), cobalt (Co, water), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), tin (Sn, water), zinc (Zn), vanadium (V), polyaromatic hydrocarbons (PAH), dioxins and furans (PCDD/-F), phenols (water), tributyltin ($C_{12}H_{28}Sn$, water)	Sleeswijk et al. 2008; Seppälä 2008
Particulate matter	Nitrogen oxides (NO_X), sulphur dioxide (SO_2), ammonia (NH_3), particulate matter (PM_{10})	Van Zelm et al. 2008
Abiotic resource depletion	Aluminum (Al), barite, chromium (Cr), cobalt (Co), copper (Cu), fluorspar, iron (Fe), lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), phosphorus (P), rhenium (Re), silver (Ag), sodium sulfate, sulfur (S), talc, tin (Sn), vermiculite, zinc (Zn), oil, coal, brown coal, natural gas, peat	Van Oers et al. 2002

> information from Valtonen's thesis (2005). The sewage sludge would be composted instead. Sewage sludge was intended to replace peat in soil amendment at a ratio of 1:1, and negative emissions would be calculated for this use. Inputs and outputs of the composting process were taken from a report by Myllymaa and colleagues (2008).

Since there are many different ways to produce heat, a second reference system was designed in order to reflect the sensitivity of the results to the selected fuel. Thus, in *Reference system 2*, everything else remains the same as in Reference system 1 except that the town would use heat that was assumed to be produced with peat instead of using average heat from Kymenlaakso. Peat was chosen for the comparison because it is a domestic fuel and the third most used fuel in heat production in Kymenlaakso (Finnish Energy Industries 2006). Data on heat produced with peat were taken from the Myllymaa and colleagues report (2008). The harvesting of the peat was also taken into account.

Potential Improvements to the Case Study IES (Reference System 3)

A further scenario, *Reference system 3*, was constructed in order to analyze the waste and emission flows of the case study IES in order to identify additional possibilities for links between the actors or for links to new actors. The potential environmental benefits of these connections were assessed in relation to the present situation. These possible new features of the symbiosis included utilization of hydrogen gas from the chlorine dioxide plant in a new hydrogen plant in the IS, use of fly ash from the power plant in forest fertilization, and treatment of municipal wastewaters from the municipality of Kouvola at the pulp and paper mill. In addition, the potential to use the waste heat from the pulp and paper mill in greenhouses was assessed. Assumptions concerning the aforementioned are presented in more detail below. However, it should be emphasized that the options studied here are hypothetical and do not imply that they would actually be considered for implementation.

The chlorine dioxide plant produces approximately 28 kilograms (kg) of hydrogen per ton of chlorine dioxide produced. This hydrogen could in principle be utilized in energy production. The same company has built a hydrogen-utilizing energy unit in its chlor-alkali plant in southeast Finland. If such a hydrogen plant were built within the case study IES, it could potentially replace 22,000 GJ of natural gas.[6]

Approximately 13,700 tons of fly ash from the power plant was deposited in landfill in 2005. This fly ash could be utilized as a forest fertilizer. Wood ash has been found to be beneficial particularly on peat lands because the ash includes phosphorus and potassium in appropriate proportions. There is no nitrogen in the ash, but nitrogen is not usually required on peat lands because peat itself contains enough plant-available nitrogen (Rinne 2007). The popularity of forest fertilization has been increasing in Finland during the 2000s, and the National Forest Programme 2015 includes a target of increasing the amount of fertilized forests from the current approximately 25,000 hectares (ha) to 80,000 ha in 2015 (Ministry of Agriculture and Forestry 2008; Finnish Forest Research Institute 2004). Thus, there arguably exists an increasing demand for forest fertilizers. According to Korpilahti (2003), 500 kg/ha of commercial fertilizer provides 45 kg phosphorus per hectare. In order to gain the same amount of phosphorus from ash, 3,000 to 7,000 kg of ash is required. In this study it was assumed that 5 tons of fly ash from the power plant would replace 500 kg of mineral fertilizer. Data on phosphorus fertilizer production were taken from the U.S. Life Cycle Inventory database (National Renewable Energy Laboratory 2008). Altogether, approximately 2,500 to 3,000 hectares could be fertilized with the currently landfilled ashes of the case study IES. Energy use and emissions generated in the process of spreading the ash were not taken into account.

A study has been conducted on the possibility of treating the wastewaters from the municipality of Kouvola at the UPM Kymi pulp and paper mill's wastewater treatment plant (Valtonen 2005). In that study, the resulting potential savings in nutrients and other chemicals were calculated. The sewage sludge from the municipal wastewater treatment plant is already being delivered to the Kymi mill. According to Valtonen (2005), if the wastewater from both plants were treated together, no phosphorus would need to be added to the system and the use of urea could be reduced to 300 tons/year from the present 500 tons/year. Moreover, the ferrous sulfate ($FeSO_4$), poly-aluminum chloride, and other resources that are used in phosphorus removal at the municipal wastewater treatment plant would no longer be needed. The combined treatment would reduce the total nitrogen emissions of both plants by almost 50% and the phosphorus emissions by approximately 10% (Valtonen 2005). It was concluded in the study that despite the investment costs this combined treatment would need, the option would be cheaper for the town in the long run.

The total heat load from the case study IES that is annually released to the surface waters is approximately 2,500 GWh. It was assumed that some of this waste heat could be utilized in greenhouses, and emissions savings were thus calculated. In 2005, approximately 4.5% (based on production area) of the total Finnish greenhouse production was located in the Kymenlaakso region (Ministry of Agriculture and Forestry 2006). Of this, the greenhouses located in municipalities close to Kouvola accounted for approximately 40%. The total energy use of greenhouses was approximately 2,000 MWh in Finland in 2004 (Hiltunen et al. 2005). If the waste heat from the Kymi pulp and paper mill could cover the total energy needs of the greenhouses close to Kouvola, they would use approximately 35 MWh of its waste heat. The most common energy source in the Finnish greenhouses at the beginning of the 2000s was heavy fuel oil (Hiltunen et al. 2005), so the waste heat was taken to replace heat produced with heavy fuel oil. Data on heavy fuel oil energy were taken from the Ecoinvent database.

Results

Impacts of the Case Study IES

When looking at the normalized environmental impacts, acidification had the highest values,[7] 3.27 E-04, followed by terrestrial eutrophication, tropospheric ozone formation (human health impacts), climate change, impacts on particulate matter formation, and aquatic eutrophication. For terrestrial eutrophication, the normalized values were approximately 40% smaller than acidification impacts. The normalized impacts of climate change, particulate matter formation, and aquatic eutrophication were 60% to 80% smaller than acidification impacts. Most of the acidification, terrestrial eutrophication, and tropospheric ozone formation originated from the emissions of nitrogen oxides. Most of the NO_X emissions were generated by the pulp and paper mill, the power plant, production and transportation of hardwood, and transportation of kaolin and calcite. According to the normalized values, the impacts were 1.21E-6 to 8.05E-6 for the toxicity impact categories and 1.95E-6 for abiotic resource depletion. Thus, the normalized values for toxicity and abiotic resource depletion were very small compared with the other impact categories and were omitted from the figures presented below.

When studying the contribution of different life cycle stages (raw material extraction and processing, energy and fuel extraction and production, production within the IES, waste management processes, and impacts avoided through recovered materials) one can see that the raw material extraction and processing made the largest single contribution to the results in most impact categories (figure 2). Fuel production and energy generation contributed approximately 19% to the climate change impacts. Its contribution to the other impact categories ranged between 3% and 15%. The shares of waste management and impacts avoided through waste recovery were very small, less than 1.5% in all impact categories. As could be expected, given the large size of the pulp and paper mill, over 60% of all impacts except for terrestrial ecotoxicity impacts were caused by the mill and the upstream processes related to it. Of the total impacts of the pulp and paper mill, upstream processes caused 70% to 80% of the total impacts in most impact categories. Of the particulate matter impacts, the share of upstream processes was 60% and that of the toxicity impacts was over 90%.

Impacts of the Reference Systems

The comparison of the case study IES to Reference systems 1 and 2 indicates that the environmental impacts of the reference systems are higher in most impact categories (figure 3 and table 2; please also see tables S-1 and S-2 in the supporting information on the Journal's Web site for the detailed inventory results). The results show that in Reference system 1, impacts on climate change would increase by 12% and those on acidification and particulate matter by approximately 5%. Reference system 2 would result in larger changes in all the impact categories, particularly in acidification, which would grow by almost 40%. The other impacts, except for aquatic eutrophication, would increase by 10% to 20%.

The assumed increases in the recycling of byproducts generated by the case study IES (Reference system 3) would result in an almost 30% decrease in the aquatic eutrophication impacts (see figure 3). The other impacts would decrease by less than 10%.

The sources of aquatic eutrophication, particulate matter formation, acidification, and terrestrial eutrophication were studied in more detail (figure 4). The largest contributors to these impacts except for aquatic eutrophication, in both the case study IES and the reference systems, throughout the whole life cycle of the production system were the pulp and paper mill, the power plant, the production of potato starch, optical brighteners, and sodium hydroxide, transportation of kaolin and quicklime, and production of hardwood. The pulp and paper mill and the power plant are represented as the source of direct

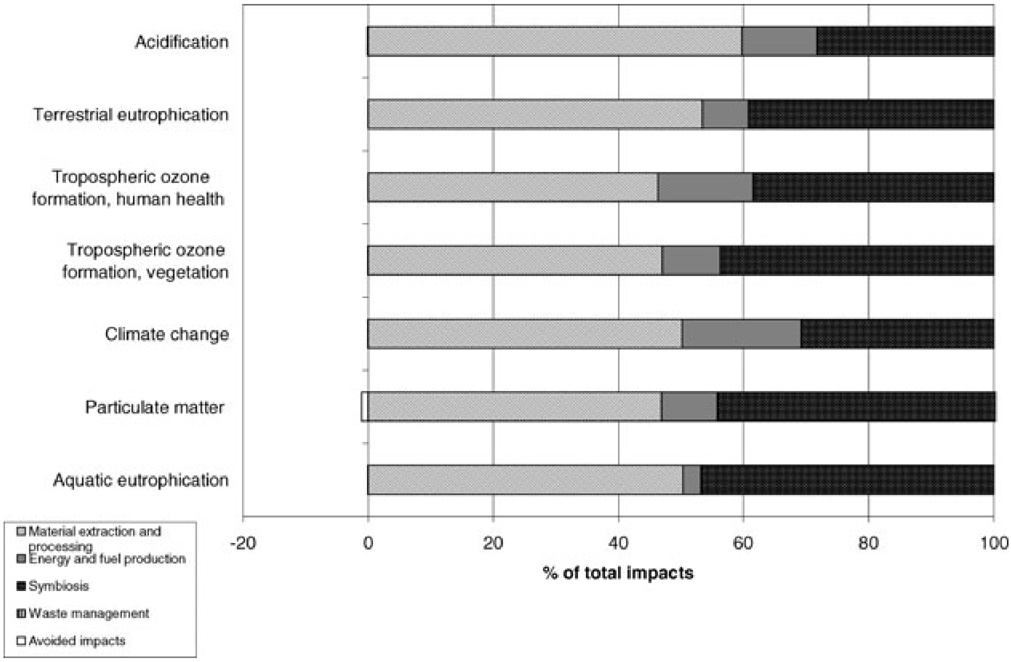

Figure 2 Normalized values according to different life cycle phases in the case study industrial ecosystem. Energy and fuel production includes extraction of fuels. Normalized values for freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity, and abiotic resource depletion were so small that they were omitted from the figure. The contributions of the life cycle phases waste management processes and impacts avoided are so small that they are not visible in the figure except for the small contribution of impacts avoided in particulate matter formation. Symbiosis stands for inputs to and outputs from the symbiosis.

emissions of the case study IES, while the other processes are represented as upstream processes. The largest contributors to the aquatic eutrophication impacts in the case study IS and Reference systems 1 and 2, were the municipal wastewater treatment plant (Akanoja sewage plant in figure 4a) and sodium hydroxide production. There are no emissions from the municipal wastewater treatment plant in Reference system 3 since in Reference system 3 municipal wastewaters are treated at the pulp and paper mill. Approximately 35% of the reduction in aquatic eutrophication impacts is caused by the combined treatment of wastewaters at the pulp and paper mill (direct emissions of the IES), while the rest of the reduction is caused by the replacement of added phosphorus and nitrogen at the pulp and paper mill with sewage sludge and the utilization of wood ash in forest fertilization (upstream processes).

The role of optical brighteners in particular was perhaps surprisingly high considering that the amount used was fairly small: 1,550 tons (100% purity). The production of optical brighteners is very energy intensive compared with that of some other bleaching chemicals such as H_2O_2, but on the other hand, the amount of chemicals needed is much lower (Scheringer et al. 1999). One can see that the role of transportation of kaolin, quicklime, and hardwood was fairly large as well; altogether they accounted for 9% to 15% of the total impacts.

The difference in environmental impacts between Reference systems 1 and 2 and the case study IES is mainly attributable to the differences in energy production. In the reference systems, emissions from the power plant, which especially affect impacts related to NO_X emissions, decrease (see table 2). At the same time, emissions from the average production of district heating

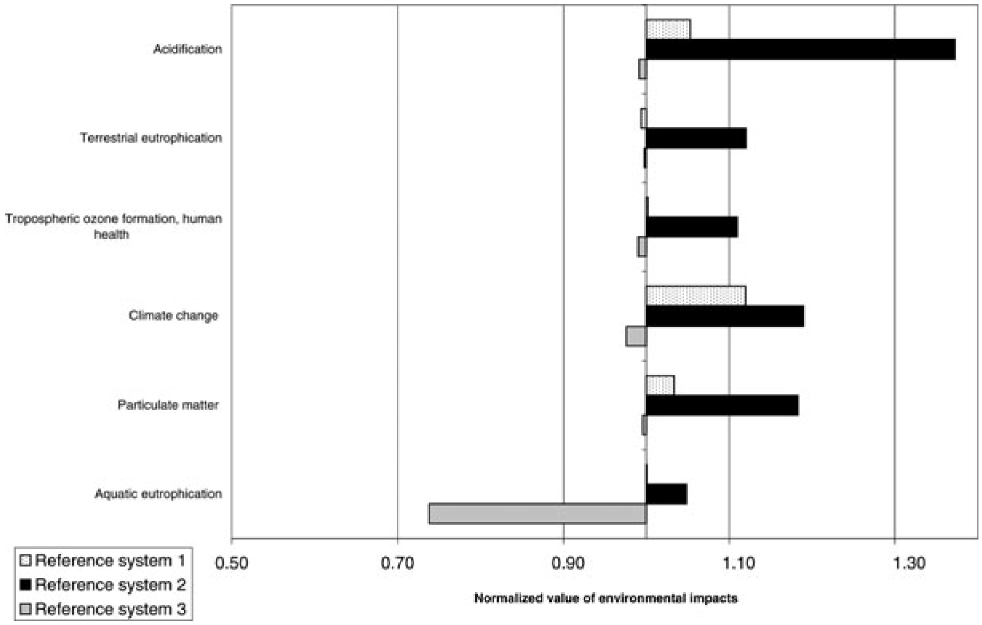

Figure 3 Environmental impacts of the reference systems in relation to those of the case study industrial ecosystem (IES) (the environmental impacts of the IES get the value 1). Normalized values for freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity, and abiotic resource depletion were so small that they were omitted from the figure.

and electricity increase. This impacts the CO_2 emissions in particular. Moreover, in Reference system 2, in which more peat is used, CO_2, NO_X, and SO_2 emissions from energy production increase. Thus, it can be concluded that in Reference systems 1 and 2 the contribution of upstream processes to the total impacts is higher than in the case study IES. This is mainly because in

Table 2 Absolute and Relative Differences in the Main Emissions and Consumption of Fuels Between the Case Study Industrial Ecosystem and Reference Systems 1, 2, and 3

	Case study IES	*Difference from reference system 1*	*Difference (%)*	*Difference from reference system 2*	*Difference (%)*	*Difference from reference system 3*	*Difference (%)*
CO_2	6.20E+08	7.59E+07	12%	1.27E+08	21%	−1.47E+07	−2%
CH_4	1.30E+06	1.17E+05	9%	−6.77E+04	−5%	−8.22E+04	−6%
N_2O	4.99E+04	3.42E+03	7%	1.29E+03	3%	−4.84E+01	0%
NO_X	3.02E+06	−2.94E+04	−1%	4.25E+05	14%	−1.24E+04	0%
SO_2	1.31E+06	1.88E+05	14%	9.71E+05	74%	−3.18E+04	−2%
PM_{10}	5.41E+05	1.95E+04	4%	−1.03E+04	−2%	−9.89E+02	0%
NMVOC	4.32E+05	5.74E+03	1%	−5.61E+03	−1%	−5.85E+03	−1%
NH_3	1.06E+05	−2.80E+02	0%	−1.68E+03	−2%	−6.74E+02	−1%
Nwater	4.83E+05	8.12E+02	0%	3.53E+03	1%	−9.09E+04	−19%
Pwater	5.40E+04	4.21E+02	1%	9.82E+02	2%	−3.27E+04	−61%
Oil	5.38E+07	4.90E+05	1%	5.06E+05	1%	−4.24E+07	−79%
Hard coal	4.79E+07	1.36E+07	28%	3.45E+06	7%	−1.69E+04	0%
Natural gas	9.94E+07	1.95E+06	2%	−5.88E+06	−6%	−7.22E+06	−7%

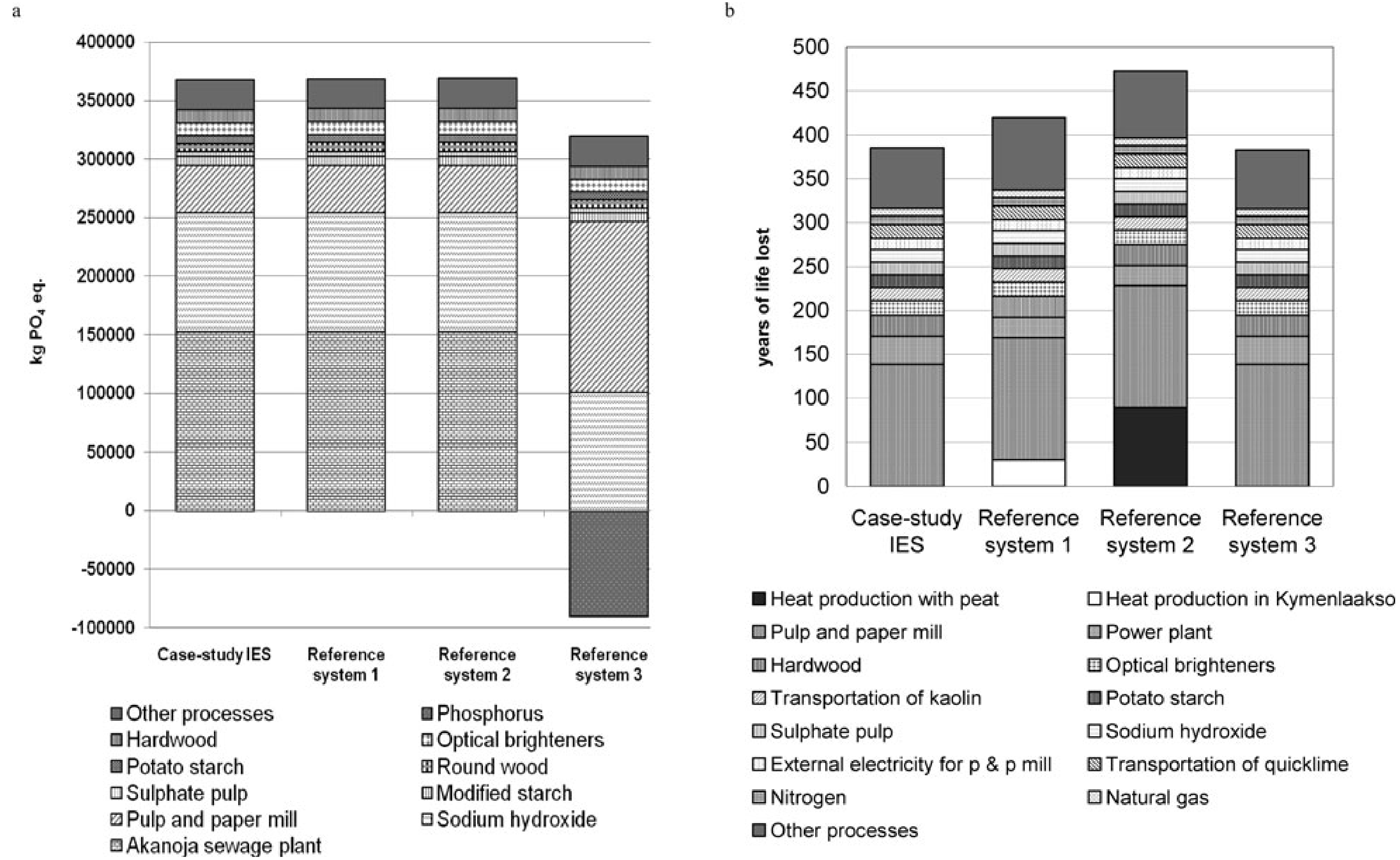

Figure 4 Comparison of the contribution of different processes in different reference scenarios and in the case study industrial ecosystem to the most important impact categories caused: (a) aquatic eutrophication; (b) particulate matter formation; (c) acidification; and (d) terrestrial eutrophication.

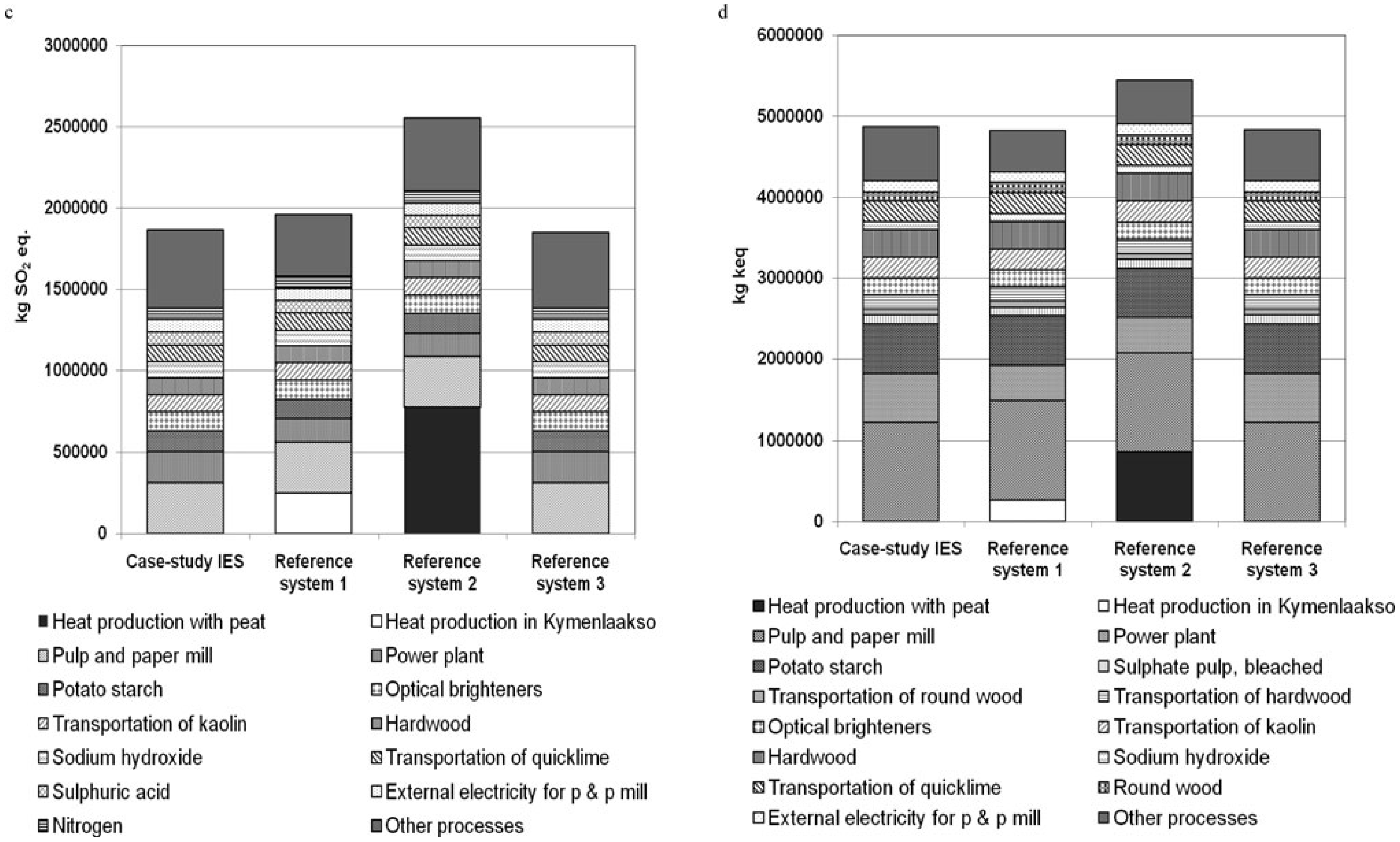

Figure 4 Continued

the reference systems the power plant does not supply the local town with heat and electricity. Therefore, the town needs to purchase electricity and heat from other sources, which leads to higher upstream emissions. Carbon dioxide emissions also grow because the pulp and paper mill no longer delivers part of its CO_2 to the calcium carbonate plant. The significance of the other processes is minor.

The reduction in aquatic emissions and thereby aquatic eutrophication impacts in Reference system 3 is due to the treatment of municipal wastewater at the case study IES and replacement of phosphorus fertilizer through utilization of wood ash in forests. Large reductions in the system's environmental impacts could potentially be achieved if more of the waste heat from the pulp and paper mill could be utilized. However, at present such heat is not being used anywhere on a large scale. In the analysis it was assumed that a small proportion of it could be utilized in the heating of greenhouses.

Sensitivity Analysis

The main uncertainties of this study relate to the data on upstream processes. The amount of raw materials, fuels, and energy used was received directly from the actors of the case study IES and is fairly accurate, but the data on the production of these materials and fuels are mainly generic, originating from different databases, and do not necessarily represent the actual production processes. Therefore, the data sources of those upstream processes contributing most to the results were varied in the sensitivity analysis. Four different scenarios were constructed:

- In Scenario 1, external electricity purchased by the pulp and paper mill was assumed to represent the electricity profile of the Finnish forest industries in 2007 (Finnish Forest Industries Federation 2009).
- In Scenario 2, the transportation distance of kaolin was changed. On the basis of information about the producers it was originally assumed that one third of the kaolin originated in the United States and two thirds in the United Kingdom. Transportation mode was assumed to be a roll-on ship by sea and fully loaded Euro3 truck on land. For the sensitivity assessment, we assumed that all the kaolin was imported from the United Kingdom. Transportation mode was assumed to be the same.
- In Scenario 3, the data source of optical brighteners was changed. Instead of using the Ecoinvent Database version 2.01 (Swiss Centre for Life Cycle Inventories 2007), data from the article by Scheringer and colleagues (1999) was used.
- In Scenario 4, it was assumed that the pulp and paper mill used maize starch instead of potato starch. Data on maize starch were taken from the Ecoinvent database version 2.01 (Swiss Centre for Life Cycle Inventories 2007).

The impact of these factors was less than 15% on most of the main emissions (table S-3 in the supporting information on the Web) and less than 10% on the main impact categories (figure 5) for all scenarios. The greatest changes were caused by Scenario 3, which resulted in an 8% decrease in the acidification impacts and a 5% decrease in the terrestrial eutrophication impacts.

Discussion

In this study, normalized LCA results were presented and no weighting was applied to the impact categories. Normalized values can be judged to rank the impacts in their order of importance provided that all environmental effects are considered equally important; for example, the significance of total current levels of global warming and toxicity effects would be assumed to be equal (Pennington et al. 2004). However, one must be aware that different valuation studies indicate that not all the environmental impacts are generally considered equal in importance (e.g., Seppälä 2003), so special care must be taken when comparing normalized values across impact categories.

The study showed that the impacts occurring outside the IES may be high. We did not find other evidence for this from the literature, but

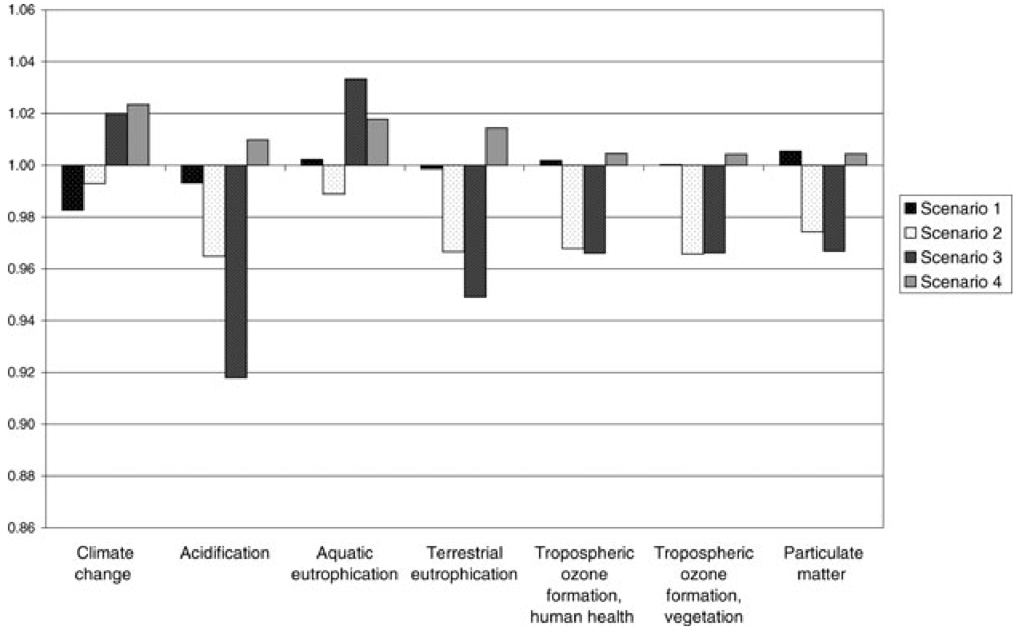

Figure 5 Sensitivity of the main impacts to the different scenarios.

similar results have been reported for different kinds of systems. For example, the environmental impacts of the Second Sydney Airport proposal were assessed by extending environmental impact assessment with input-output analysis to cover effects occurring off-site (Lenzen et al. 2003). The results showed that indirect impacts were considerable for all the factors studied. Matthews and colleagues (2008) presented the same conclusion for carbon footprints. Thus, one implication of our study is that when developing or initiating an industrial symbiosis, the analysis should be extended to off-site impacts as well, as these may be decidedly high in relation to impacts within the symbiosis. Singh and colleagues (2007) concluded in their study that LCA is an extremely useful tool for analyzing and comparing different designs of industrial symbioses. Similarly, LCA can be applied when looking at industrial symbioses already in operation.

The results indicate that in the present case the environmental impacts are smaller from the system operating as an industrial symbiosis than from stand-alone production. The difference was the greatest in acidification, climate change impacts, and impacts on particulate matter formation. Reduction in the environmental impacts was primarily caused by energy production for Kouvola town. However, as it was also found in the study that the upstream processes made a considerable contribution to the overall results, it may be concluded that the greatest reductions in the overall environmental performance of the system can be achieved by minimizing the total raw material use of the system. However, here it was assumed that the pulp and paper mill gets most of its electricity and heat from wood-based fuels also in the stand-alone situation. Assuming that it would either buy wood from outside the system or use fossil fuels instead would have increased its environmental impacts throughout.

It can be argued that a central environmental driver for IES is the increased material efficiency through recycling and the resulting avoidance and reduction of upstream effects of resource extraction and primary production. The value of LCA lies in the possibility to locate those flows whose reduction provides the greatest overall environmental benefits. For example, it can be used to locate areas of improvement or to assess the environmental benefits of additional symbiotic links. As Reference system 3 of our study showed, the greatest additional environmental benefits could be achieved through combined treatment of wastewaters of the municipal wastewater treatment plant and the pulp and paper mill, replacement of nutrients with the municipal sewage sludge, and utilization of wood ash for forest fertilization.[8] Approximately 35% of these benefits were achieved with respect to the direct emissions of the case study IES and the rest in the upstream processes. The contribution of the other processes was minor. It should, however, be pointed out that additional reductions in the overall environmental performance of the system could be achieved through more efficient technology and changes in the fuel mix used.

Significant reductions in the system's environmental impacts could potentially be attained if more of the waste heat from the pulp and paper mill could be utilized. Fish farms have also been noted as potential users of waste heat (Lowe and Evans 1995). However, in Finland their total energy use is fairly low (Silvenius and Grönroos 2004). In the future, more potential could perhaps be found in the drying of wood pellets. The drying process is usually the most energy-demanding phase of pellet production (Andersson et al. 2006; Sokka et al. 2009). This option, however, was not studied further as only options that were actually in use somewhere were chosen for the reference systems. Moreover, until recently, the production of wood pellets has been fairly small in Finland, totalling 192,000 tons (3.2 TJ) in 2005, of which over two thirds were exported (Statistics Finland 2006). However, policy targets have been set to increase the use of renewable fuels, and the Finnish long-term climate and energy strategy aims to increase the use of pellets in industry and housing by 2020 (Council of State 2008).

The main uncertainties in this study related to the data on upstream production processes. The amount of raw materials, fuels, and energy used was received directly from the actors of the case study IES and was fairly reliable, but the data on upstream processes were mainly generic, originating from different databases, and do not necessarily reflect the actual production processes. Thus, in the sensitivity analysis, data sources of those upstream processes with the greatest impact on the results were studied. In addition, the transportation distance of kaolin was varied. The different scenarios resulted in fairly small changes, less than 10% in all impact categories compared with the case study IES.

One major uncertainty concerning the comparison with stand-alone production is that it is not clear how the stand-alone situation should be defined. A symbiotic mode of operation is very typical for the Finnish forest industry. We tried to find the most realistic scenario of how the actors would operate in a stand-alone scenario choosing a situation that does actually occur elsewhere. However, the choice is subjective and is open to question. We assumed that even in a stand-alone situation the energy production of the pulp and paper mill would be based on utilizing its own wood residues and black liquor, as is generally the case in the Finnish forest industry (Finnish Forest Research Institute 2006). The situation would have been different if we had assumed that wood was not used as an energy source at the pulp and paper mill. However, this assumption was made because it is a common practice in the forest industry in Finland and abroad.

The study method used was a traditional LCA, which necessarily results in upstream and downstream cut-offs. In recent years, so-called hybrid methods, where product-based LCA is combined with input-output accounting, have increasingly been used (for a review of the hybrid methods, see Suh and Huppes 2005). Because we studied the applicability of LCA for analyzing the environmental impacts of an industrial symbiosis and compared the impacts of the industrial symbiosis to separately operating systems and assessed the upstream processes in relation to processes occurring within the symbiosis, applying a full-scale hybrid LCA was not considered necessary.

Concluding Remarks

In the case studied, comparison with the stand-alone production showed that the symbiosis resulted in net improvements in the total environmental impacts of the system, the difference being between 5% to 20% in most impact categories. The difference was the greatest in acidification, climate change impacts, and impacts on particulate matter formation. Reduction in the environmental impacts was primarily caused by energy production for Kouvola town.

Symbiotic exchanges reduce the need to purchase raw material and energy from outside the symbiosis. Efficient energy production and utilization are critical factors contributing to the overall environmental performance of symbiosis-like production systems. In the case study IES, upstream processes made a considerable contribution to the overall results. Thus, it may be concluded that major reductions in the total environmental impacts of the system can be achieved by affecting the extraction and production of raw materials and external energy. All in all it is recommended that when assessing the environmental performance of an industrial symbiosis or an eco-industrial park, the impacts occurring upstream should be studied and not merely the situation within the symbiosis. LCA seems a very useful, albeit labor-intensive, tool for this kind of assessment. It can also help in detecting those flows whose utilization could provide the greatest environmental benefits.

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Notes

1. In this article the term *industrial symbiosis* refers to the collection of exchanges and processes that occur within a system called an industrial ecosystem.
2. The VAHTI database is an emissions control and monitoring database of the Finnish Environmental Administration.
3. Ecoinvent: www.ecoinvent.ch
4. www.vtt.fi/research/technology/sustainability_assessment.jsp?lang=en
5. In reality, it would probably be difficult to obtain enough liquid CO_2 available to replace the CO_2 received in flue gas (Taskinen 2008).
6. The heating value of hydrogen is assumed to be 120 megajoules per kilogram (U.S. Department of Energy 2006).
7. In Finland, natural systems are particularly vulnerable to acidification due to the low buffer capacity of the soil. Therefore, the importance of acidification impacts tends to become high in studies using Finnish-specific characterization factors.
8. The possible impacts that such a cheap phosphorus source would have on the domestic phosphorus markets were not assessed in this study. On the other hand, phosphorus is a limited resource, and with the increase of food and biofuel production, serious concerns have been raised on its long-term availability (Lewis 2008).

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1. This supporting information contains tables showing the inventory results for the symbiosis case and reference systems and the sensitivity of the main emissions to the different scenarios.

PAPER IV

Quantifying the Total Environmental Impacts of an Industrial Symbiosis

A Comparison of Process-, Hybrid and Input–Output Life Cycle Assessment

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Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid and Input−Output Life Cycle Assessment

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Industrial symbiosis, representing resource sharing and byproduct use among colocated firms, is a key concept of industrial ecology. Local co-operation in industrial symbioses can reduce raw material use and waste disposal, but material and energy flows extending outside symbiosis boundaries can cause considerable environmental impacts. These external impacts are often ignored in industrial symbiosis studies. In this study, we compared process, hybrid and input−output life cycle assessment (LCA) approaches in quantifying the overall environmental impacts of a forest industrial symbiosis, situated in Kymenlaakso, Finland. Conclusions from an earlier process-LCA were strengthened by the use of hybrid-LCA as local emissions were found to cause less than half of the global impacts. In some impact categories, the whole impact was caused by supply chain emissions (land use, metal depletion and ozone depletion). The cutoff in process-LCA was found to be less than 25%, except in metal depletion and terrestrial ecotoxicity. Input−output LCA approximated hybrid-LCA results well in most impact categories, but seriously underestimated land use and overestimated terrestrial ecotoxicity. Based on the results we conclude, that input−output based LCA can be used to analyze the global impacts of an industrial symbiosis, but a careful interpretation of the results is necessary in order to understand the influence of aggregation and allocation.

Introduction

Industrial Symbiosis in Forest Industry. Eco-industrial parks (EIP) and industrial symbioses (IS) are key concepts of industrial ecology (IE). In an EIP or IS a group of local companies and communities share energy, water, byproduct and waste treatment (*1, 2*). The goal of such arrangements is both to improve economical efficiency and to minimize the use of external raw materials and produced waste. When at least three companies exchange at least two commodities, these exchange networks are called industrial symbioses (*3*). While some symbioses have been designed for environmental efficiency, most have self-organized to optimize the use of scarce resources (*3*).

Scandinavian forest industries have spontaneously developed a high proportion of byproduct sharing and combined energy production (*4*). In a typical setup a pulp and paper mill is surrounded by a power plant, several chemical plants, waste management facilities and sewage treatment plants. Often the industrial park provides heat and power to a local town (*5*).

Process, Hybrid and Input−Output Life Cycle Assessment for Environmental Impact Assessment. Most literature on industrial symbioses has focused on the direct impact within the industrial symbiosis and possibly a few tiers up the supply chain (*6, 7*). Environmental benefits have been quantified by comparing material and energy flows between an existing symbiosis and a hypothetical reference case, where the companies would not exchange byproduct (*6*). However, when analysis is limited to direct and energy related emissions, it is subject to cutoff errors. In an average industry in the U.S. the carbon dioxide emissions from operation and direct energy supply amount to one-fourth of the total emissions produced throughout the supply chain (*8*). Estimating potential benefits of the symbiotic operation based on such a limited scope is expected to produce erroneous results. Therefore the analysis of the environmental benefits of an industrial symbiosis should include impacts caused in the global supply chain outside the symbiosis itself (*7*).

Ideally a process based life cycle assessment (process-LCA) captures all environmental impacts by following supply chains from cradle-to-grave (i.e., from material extraction to returning of wastes to nature) (*9*). In practice it is constrained by time and resource limitations, and parts of the system are usually neglected or cutoff from the analysis. The impacts of this cutoff are reported to be about 20% for many impact categories (*10*) and considerably larger for the raw materials stage in some product systems (*11*) especially in capital intensive sectors (*12*).

In hybrid life cycle assessment (hybrid-LCA), the environmental impacts of flows which were not included in the process-LCA are estimated with an environmentally extended input−output model (*13, 14*). Such an input−output table can also be used to construct an input−output life cycle assessment (IO-LCA) without using any process based life cycle inventories (*15*).

As the input−output model is constructed from national accounts, it contains the whole national economy as well as imports. Therefore cutoff is eliminated. However, uncertainty may be increased through aggregation of several products to sectors, monetary transitions between currencies and times, and possible use of outdated data on industrial interactions and emissions (*10, 16*). For example, one of the most used input−output tools was only recently updated to 2002 data, prior to that update it represented the technology and emission intensities of the U.S. economy in 1997 (*15*). However, also process-LCA is subject to using outdated data and the cutoff associated with process-LCA may be a larger source of error than the aggregation errors of IO-LCA (*10, 16*). In spite of limitations, hybrid-LCA is considered to be the state-of-the art method in life cycle assessment (*17*), combining the accuracy of process-LCA with the completeness of IO-LCA. For optimal use of the three approaches, some authors recommend performing a quick IO-LCA first, followed by an extraction of the most important pollutant pathways from it (with structural path analysis) for detailed process-LCAs (*17, 18*).

In this study, the environmental sustainability of an industrial symbiosis centered around a pulp and paper mill (situated in Kymenlaakso, Finland) was assessed by supplementing previous process-LCAs (*19, 20*) with a tiered hybrid analysis (*13, 14*). Cut-off flows from the earlier assessments

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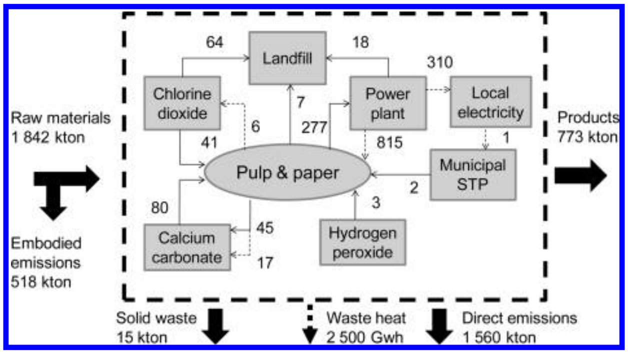

FIGURE 1. Aggregated material and energy flows in the case symbiosis drawn from data in refs *19, 20*. Material flows (solid lines) are in kilotons and energy (dotted lines) in GWh. Purified water and wastewater were excluded from this figure, since they would have dominated the material flows.

were estimated from Finnish environmentally extended input−output tables describing year 2005 (*21*). The purpose of this analysis was to see the limitations of process LCA in the environmental assessment of industrial symbioses through quantifying the amount of cutoff left in a thorough process-LCA. In addition an IO-LCA was made in order to see if key environmental issues could be accurately identified with a less time-consuming method than process-LCA.

Material and Methods

Description of the studied industrial symbiosis. The studied symbiosis (situated in Kymenlaakso, South-Eastern Finland) contains five interconnected industrial facilities centered around a pulp and paper mill (*19, 20*). The pulp and paper mill was initially founded in 1872 by the Kymijoki River. Over time the symbiosis has extended to include chlorine dioxide, calcium carbonate and hydrogen peroxide plants, a power plant, and a landfill (Figure 1). In addition, the pulp and paper mill has incorporated power production, water purification and wastewater treatment systems, providing services for the industries and the municipality. The symbiosis produced 773 000 tons of products in 2005, of which 720 000 was paper (c.a. 7% of annual Finnish paper production).

The byproduct reuses and resource sharing between plants of the symbiosis (Figure 1) forms the industrial symbiosis (*3*). A detailed description of the energy flows is given in ref *20*, therefore only the main flows are described in the following paragraph. The pulp and paper mill is the core of the system, supplying electricity, heat, steam and purified water to the chemical plants and treating wastewater and municipal sewage sludge. In addition it produces energy from black liquor and provides 277 kt (kilotons or Gg) of wood based fuel to the power plant. The power plant in turn supplies 815 GWh of heat and steam to the pulp and paper mill and 310 GWh of electricity to the municipality. The calcium carbonate plant uses 45 kt of carbon dioxide and 17 GWh of energy from the pulp and paper mill to supply 80 kt of products to the pulp and paper mill and 26 kt for external sales. Similarly the chlorine dioxide plant uses purified water and energy to supply 41 kt of chlorine dioxide and sodium hydroxide to the pulp and paper mill. Solid waste is treated in the industrial landfill operated by the pulp and paper mill. Apart from these main flows, there are some small byproduct exchanges with operators outside the symbiosis, such as waste lime use as agricultural fertilizer. Further details of the exchanges are presented in the previous life cycle assessment of the symbiosis (*19*).

Process-LCA Inventory Collection and Impact Assessment. The hybrid analysis builds upon the previously published process-LCA of the symbiosis (*19, 20*). The inventory was collected for the year 2005 according to ISO 14040 on LCA. The product system included the production of raw materials, fuels and electricity used in the symbiosis, as well as transportation and management or recycling of the main waste materials. Since the products of the park were intermediate products of other industries, the analysis was focused on the upstream life cycle and the subsequent possible uses and disposal options for the products were ignored (i.e., cradle-to-gate analysis). Physical flows within the symbiosis (raw materials, fuels, emissions, and wastes) were collected from companies, and their environmental permits and reports, and from the national emission control and monitoring database (VAHTI, Finnish Environment Administration). Emissions and natural resource use associated with raw material manufacturing, recycling and waste treatment were collected from available LCA databases, mainly the Swiss Ecoinvent database and from the sources used for direct emission estimation (for more details see ref *19*).

Environmental impacts of individual emissions and resource depletion were assessed with the LCIA-RECIPE method (*22*), which is an update of the commonly used CML method (*9*). Impacts to climate change, acidification, eutrophication, ecotoxicity, human toxicity, ozone depletion, land use, and depletion of fossil fuels and metals were quantified by multiplying individual emissions and resource extractions with a corresponding characterization factor (derived by linearization of an impact assessment model) (*9, 22*). Water use and ionizing radiation were excluded from the method due to lack of inventory data (both in the life cycle inventory and in the national accounts). The RECIPE method provides characterization factors for both midpoint and endpoint impacts. Endpoint results describe damage to three areas of protection (human health, ecosystem quality and resource depletion), while midpoint results describe separate impact categories such as eutrophication or climate change (*22*). In this study impacts were assessed at the midpoint level since it has less uncertainties and value choices than the endpoint level (*22*). Characterization factors representing current sustainability policies were selected (i.e., climate change is assessed with a 100 year time frame and toxic effects are assessed for an infinite time period). The different impact categories were normalized by dividing each category result with the corresponding impact of an average European citizen (*23*).

Environmental Input−Output Analysis Based Inventory. An input−output based inventory (IO-LCA) was produced by using environmental multipliers instead of process-LCA data sets to quantify the emissions from the supply chain of the symbiosis. The raw material and energy flows documented in the process-LCA were changed into monetary purchases from economic sectors and then weighted with the corresponding emission multipliers.

An environmentally extended input−output table of Finland was used for the multipliers. The model included monetary flows and emissions for the years 2002 and 2005 as well as the physical input−output table (PIOT) for the year 2002. As details of the model are currently available only in Finnish (*21*) a brief description is given here. The industry-by-industry table had 150 industries and was constructed from the national 178 industry by 918 product use and make tables (*24*) using the fixed product sales structure assumption as recommended by EUROSTAT (*25*). Service sectors were combined and the agricultural and waste sectors were somewhat disaggregated, resulting in 150 industries. Domestic emissions were based on the national emission control and monitoring database (VAHTI, Finnish Environment Administration) and energy statistics (*26*). The emissions included nutrients, heavy metals, greenhouse gases, particulate matter, nitrous and sulphurous oxides, dioxins and furans, polycyclic aromatic hydrocarbons, and pesticides. Land use was based on the CORINE land use survey of the year 2000 and resource depletion on the mining statistics. The impacts of 722 import products were quantified by a combination of Ecoinvent process-LCA modules (*27*) and domestic emission multipliers. The emission multipliers used in this study were calculated using the methods explained for example in refs *14, 28*.

Price data was needed to convert material and energy flows of the process-LCA into economic flows needed in the IO-LCA. These prices were obtained by dividing the monetary use table of 2002 (in producer's prices) (*24*) with the corresponding physical table (*21*), and multiplying the results with the ratio of industry specific producer's price indexes for the years 2002 and 2005 (*29*). Price indexes were unnecessary for energy since energy statistics for the year 2005 (*26*) were available.

In addition to the input flows identified in the process-LCA, the use of input−output tables made it possible to include previously ignored flows such as services and maintenance. These flows were estimated from input-coefficients of the national accounts, which represent the inputs needed in a given industry to produce one unit of economic output. The material production of the industrial symbiosis was multiplied with product average producer's prices to obtain the amount of monetary output. This was then used to estimate the inputs necessary for production, if the symbiosis would operate similarly to other plants of the industry. For example the products of the pulp and paper mill (i.e., paper, pulp, bark fuel, and birch oil) were worth 584 M€. In order to produce these outputs in pulp and paper industry in 2005, on average 13 M€ of special machinery industry outputs were needed based on the input-coefficients. The embodied carbon dioxide emissions for that amount of special machinery production would be 4900 t. Similar calculations were made for each of the plants in the symbiosis, all input products and all emissions.

Since some of the inputs estimated with the IO-LCA were identified in the process-LCA a decision had to be made, how to combine the two data sets. We assumed that the material flows obtained from companies and environmental permits would represent the true amount of raw materials and energy used in the specific plant. Therefore the industry average economic flows calculated with the input-coefficients were replaced with the economic values of documented input flows. Contrary to the work of Strømman et al. (*30*), which provides a method for assessing the extent of cutoff in identified process-LCA flows, we assumed that all identified process-LCA flows would be completely identified. Therefore the input-coefficients for raw materials and energy were set to zero. This corresponds to the path exchange method of hybrid-LCA (*31*) applied only to the direct inputs into the symbiosis.

The approach had a few limitations. In the environmentally extended input−output table used in this study, capital investments were not included into the input-coefficients, but were considered as a separate category of final demand (cf. *16, 28*. for the extent of cutoff). Second, it was assumed that the product flows included in the process-LCA were included completely (i.e., all basic chemicals were included). Analytical tools for testing the completeness of inventory data (*30*) require company level price and value added data, which were unfortunately not available. However since the life cycle assessment inventory was very thorough, errors in the amounts of raw materials were assumed to be small. While capital inputs have been identified as important (*16*), infrastructure construction is rarely included in life cycle assessments (*9*). Therefore the results from both methods used in this study can be considered as accurate.

Quantifying Cutoff with Hybrid-LCA. The only difference between the hybrid-LCA and the IO-LCA described earlier is in the data sources used for assessing the impacts of flows identified in the process-LCA. While in the IO-LCA emission multipliers were used for all input-flows, in the hybrid-LCA emission multipliers were used only for cutoff flows and services. Physical flows were assessed using the same life cycle inventories as in the process-LCA.

The cutoff was subdivided into three components for analysis: upstream, substitution, and services. The upstream cutoff consisted mainly of chemicals (reported only as trade names), lubricant oils, and wood based raw materials. Substitution cutoff included cutoff flows from the product systems, which were thought to be substituted by the byproduct of the symbiosis (mainly cardboard, oils, and steel). Services included all the inputs, which were not quantified in the process-LCA, but which were estimated based on the industry average input-coefficients of the IO-LCA (i.e., repair services, machinery maintenance). It should be noted, that the component labeled as services, included also some flows, which were not services (i.e., machinery, spare parts, building materials). However services represent the majority of the economic flows in this category.

A fourth component of cutoff, downstream cutoff, was not assessed. Downstream cutoff is the increased intermediate demand of products of the process-LCA by the operation of the upstream supply chains of the same process-LCA (*13, 14*). According to ref *32*, downstream cutoff should be included when there is indication that the products of the process-LCA are widely used in the economy. As all the industries operating in the studied symbiosis (pulp and paper, chemicals, and energy) produce a large share of products for intermediate demand in the Finnish economy (*24*), downstream cutoff might have a significant contribution to the inventory. However as the functional unit of the process-LCA included the whole production of the symbiosis, including the production for intermediate demand of other industries, downstream cutoff was already included in the functional unit and was not assessed in the hybrid analysis. Therefore algorithms for removing double counting (*13*) were not considered necessary.

A summary of the data-sources in the process-, hybrid-, and IO-LCA is shown in Table 1. All approaches quantified the direct emissions within the symbiosis with the same data. Process- and hybrid-LCA used the same data for raw materials and energy, except that hybrid-LCA included some environmental input−output analysis (EIOA) based emission inventories. IO-LCA instead estimated the emissions of raw materials and electricity from the emission intensity coefficients of the EIOA. Finally both the hybrid- and IO-LCA quantified the use and impacts of monetary flows with the same industry-average input-coefficients.

Results and discussion

The Extent of Cutoff in Process-LCA. For most impact categories, the extent of cutoff (i.e., difference between hybrid- and process-LCA results) was in the published range of c.a. 20% (*10*) (Table 2). The largest cutoff was in services, except for land use. Process-LCA underestimated metal depletion and terrestrial ecotoxicity, which was mainly caused by not including the repairs (purchases of special machinery and nonferrous metals). Repair and upgrading of machinery was the third greatest monetary expenditure in the Finnish pulp and paper industry in 2005 following purchases of wood and electricity (*24*). Capital intensive production has been shown to have large amounts of cutoff also in other studies (*12*). Therefore, both economic importance and environmental impacts support the inclusion of machinery repairs into further process-LCAs, especially if the focus is on heavy industries, and metal depletion or ecotoxicity are of concern.

Freshwater eutrophication and land use were captured almost completely by the process-LCA. This was not surpris-

TABLE 1. Comparison of Data Sources and System Boundaries in the Analysis of Direct Emissions and the Three Life Cycle Assessment Approaches in This Study: Process-, Hybrid-, and IO-LCA[a]

emissions	direct	process-LCA	hybrid-LCA	IO-LCA
direct emissions	companies, permits, environmental authorities	companies, permits, environmental authorities	companies, permits, environmental authorities	companies, permits, environmental authorities
raw materials	NA	LCI database, permits, authorities	LCI database, permits, authorities, EIOT	EIOT
energy	NA	statistics, LCI database	statistics, LCI database	EIOT
services	NA	NA	EIOT	EIOT
buildings and machinery	NA	NA	NA	NA
use and disposal of products	NA	NA	NA	NA

[a] Data sources are further explained in the text. (N.A. = not assessed, EIOT = environmental input−output tables).

TABLE 2. Extent of Cut-off in Process-LCA Compared to Hybrid-LCA in Different Impact Categories[a]

			cutoff				
	DIRECT	process-LCA	upstream	substitution	services	hybrid-LCA	IO-LCA
climate change	26%	87%	6%	−2%	8%	100%	112%
stratospheric ozone depletion	0%	76%	6%	−1%	19%	100%	**68%**
terrestrial acidification	24%	88%	5%	−1%	9%	100%	80%
fresh water eutrophication	55%	92%	3%	0%	6%	100%	96%
marine eutrophication	38%	84%	7%	0%	10%	100%	104%
photochemical oxidants	36%	89%	4%	−1%	8%	100%	94%
freshwater ecotoxicity	7%	78%	5%	−1%	18%	100%	79%
marine ecotoxicity	25%	78%	6%	−3%	19%	100%	**165%**
terrestial ecotoxicity	27%	**62%**	10%	−3%	31%	100%	**241%**
human toxicity	54%	89%	3%	−1%	9%	100%	113%
particulate matter	38%	87%	3%	−1%	10%	100%	112%
metal depletion	1%	**19%**	9%	−22%	94%	100%	**155%**
fossil depletion	21%	84%	9%	−1%	9%	100%	117%
land use	0%	98%	2%	0%	1%	100%	**42%**

[a] Direct emissions within the symbiosis and input−output analysis (IO-LCA) results are also compared to the hybrid-LCA. See Table 1 for descriptions of analyses. Exceptional values are bolded.

ing, since the main inputs of the symbiosis were biological raw materials, therefore their supply chain was carefully modeled (*19, 20*). In addition, most of the impact was caused either directly by local emissions within the symbiosis (55% of eutrophication) or from immediate raw material production (land use in wood production for pulp). These results can probably be generalized to other industries where biological raw material processing is the main product, since land use and eutrophication are easily fully captured in a process-LCA.

The low amount of cutoff in the impact categories dominated by air emissions (climate change, terrestrial acidification, photochemical oxidants, particulate matter, and human toxicity) was a result of the thorough inclusion of energy use in the process-LCAs (*19, 20*). Energy related emissions were assessed up to three orders of interactions in the supply chain, therefore the good accordance cannot be generalized to simpler process-LCAs, where the captured emissions have been reported to be only $^{1}/_{4}$ of the total supply chain emissions (cf. *8*).

Comparison of Process- and IO-LCA Results. In this case study, both process- and IO-LCA gave similar overall results (Table 2), but with notable exceptions in some impact categories (Figure 2). Ozone depletion, photochemical oxidant formation, acidification, fresh water toxicity, fossil depletion, and fresh water eutrophication were predicted with similar accuracy. However, climate change, marine, terrestrial and human toxicity, marine eutrophication, particulate matter, and metal depletion were all overestimated by IO-LCA (compared to hybrid-LCA), while land use and stratospheric ozone formation were underestimated. The extent of overestimation in climate change was comparable to the underestimation in the process-LCA. In metal depletion the overestimation in IO-LCA had less bias than the underestimation in process-LCA (compared to hybrid analysis). Most notable errors in IO-LCA were found in land use and terrestrial ecotoxicity, which were misjudged by a factor of 2 (Table 2, Figure 2).

The underestimation of land use was caused by monetary allocation used in the national accounts: pulpwood was significantly cheaper than timber; therefore, most of the forest area of forestry was allocated to timber products in the emission multipliers. In comparison, process-LCI databases consider the area of forest needed to produce the wood biomass, regardless of the price or the end use. While system expansion or substitution can be included in an IO-LCA inventory collection, the input−output tables apply only economic allocation in transferring impacts from producers to consumers and embodied emissions. It can be argued, which allocation method is more appropriate: one describes material production and the other economic incentives of production. However, in using and communicating the results derived from national accounts such issues should be transparently discussed, since they differ from the allocation rules commonly used in process-LCA (*9*).

The overestimation of terrestrial and marine toxicity was caused by aggregation errors in the input−output tables. Most of the impacts were caused by purchases of lime, starch, and basic chemicals. In input−output tables, lime was aggregated with cement production, which is emission and energy intensive, but produces a cheap end product. Therefore some of the emissions of cement production were allocated to lime. Starch is a product of the grain milling industry, which has embodied pesticide emissions from

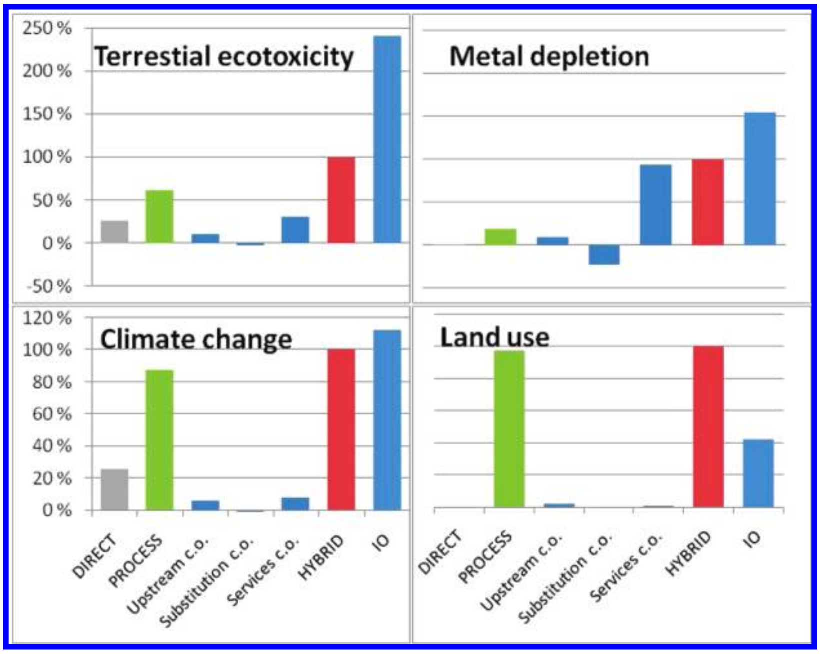

FIGURE 2. Direct local emissions, process and input−output (IO) based life cycle assessment (LCA) compared to hybrid-LCA results (set to 100%) in selected impact categories. The extent of different classes of cutoff (c.o.) between process and hybrid-LCA and the errors of IO-LCA varied depending on the impact category considered.

agriculture. In a process-LCA, grain production and starch production would be kept separate, resulting in less embodied emissions for starch. Metals caused the main toxic impact of the basic chemicals supply chain. This was problematic in two ways. First, the toxic impact of metals is currently poorly modeled in LCA (*33*). Second, aggregation and economic allocation caused errors in the IO-LCA emission multipliers for basic chemicals, which is a heterogeneous group. The case symbiosis purchased mainly polymers, calcium oxide, and lime from the basic chemicals industry. However the basic chemicals industry contained products such as industrial gases, pigments, and plastics, and purchased a considerable amount of metals. Nevertheless very little of these metals were used in polymer or lime production.

Overall good agreement was found between process-LCA and IO-LCA, which results partially from the detailed and recent nature of the environmental input−output tables used. The Finnish tables used for analysis (*21*) represented the same year 2005 as the LCA system with a resolution of 150 industries. If older or more aggregated tables would have been used, more discrepancies may have been observed (*16*).

The presence of aggregation errors and differing allocation rules limit the use of IO-LCA as a direct substitute for process-LCA in industrial symbiosis sustainability assessment. Errors in land use appropriation and metal toxicity in basic chemicals, presented in this study, demonstrate this shortfall. However if the main impact pathways are carefully examined for such errors, IO-LCA can be used as a quick sustainability assessment tool as has been found also in other studies (*10, 17, 34*).

System Boundary Influences the Relative Importance of Impact Categories. Based on the normalized results, all three life cycle methods identified land use, freshwater eutrophication, particulate matter formation and fossil fuel depletion as the most important environmental issues (Figure 3). Some differences in the absolute impact of land use, metal depletion and terrestrial toxicity can be observed between methods, but these differences have been explained in the previous chapters.

When only local direct emissions within the symbiosis boundary were taken into account, eutrophication and human toxicity were identified as the main issues, while land use and ozone depletion were ignored altogether. Land use could be quantified in local assessments if forestry operations were included into the symbiosis boundary. On the contrary, the ozone depletion category would most likely be excluded in simple assessments, since emissions are caused in the production of electronic components, which are several steps up the supply chain and outside national boundaries.

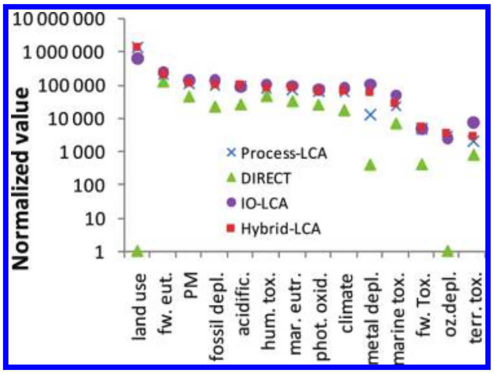

FIGURE 3. Relative importance of normalized environmental impacts of the case symbiosis depend on the boundaries of the emission estimation method. Impacts were normalized by dividing them with the annual emissions of an average European citizen (*23*).

Impacts caused by local emissions within the symbiosis amounted to less than half of all impacts (Table 2). The large influence of supply chain impacts was identified also in process-LCAs of the symbiosis (*19, 20*). A more complete inventory by hybrid- and IO-LCA methods only strengthened this conclusion. A broader analysis of industrial symbioses than previously presented (*6*) was therefore supported. In our case study, an analysis based on direct emissions only would have identified the magnitude and relative importance of environmental impacts erroneously. Overall, a supply chain based and nonregional approach for assessing the total environmental benefits of industrial symbioses was supported.

Input−output based life cycle assessment (IO-LCA) was shown to approximate more detailed hybrid-LCA results well.

Therefore it can generally be recommended as a first approach to quantifying the total environmental impacts of an industrial symbiosis. However in this case study, toxic impacts were grossly overestimated and land use was underestimated with IO-LCA. Based on the results, a careful interpretation of results derived from national accounts is necessary to properly identify possible allocation and aggregation errors.

Acknowledgments

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Author(s)
Laura Sokka

Title

Local systems, global impacts

Using life cycle assessment to analyse the potential and constraints of industrial symbioses

Abstract

Human activities extract and displace different substances and materials from the earth's crust, thus causing various environmental problems, such as climate change, acidification and eutrophication. As problems have become more complicated, more holistic measures that consider the origins and sources of pollutants have been called for.

Industrial ecology is a field of science that forms a comprehensive framework for studying the interactions between the modern technological society and the environment. Industrial ecology considers humans and their technologies to be part of the natural environment, not separate from it. Industrial operations form natural systems that must also function as such within the constraints set by the biosphere. Industrial symbiosis (IS) is a central concept of industrial ecology. Industrial symbiosis studies look at the physical flows of materials and energy in local industrial systems. In an ideal IS, waste material and energy are exchanged by the actors of the system, thereby reducing the consumption of virgin material and energy inputs and the generation of waste and emissions. Companies are seen as part of the chains of suppliers and consumers that resemble those of natural ecosystems.

The aim of this study was to analyse the environmental performance of an industrial symbiosis based on pulp and paper production, taking into account life cycle impacts as well. Life Cycle Assessment (LCA) is a tool for quantitatively and systematically evaluating the environmental aspects of a product, technology or service throughout its whole life cycle. Moreover, the Natural Step Sustainability Principles formed a conceptual framework for assessing the environmental performance of the case study symbiosis (*Paper I*). The environmental performance of the case study symbiosis was compared to four counterfactual reference scenarios in which the actors of the symbiosis operated on their own. The research methods used were process-based life cycle assessment (LCA) (*Papers II* and *III*) and hybrid LCA, which combines both process and input-output LCA (*Paper IV*).

The results showed that the environmental impacts caused by the extraction and processing of the materials and the energy used by the symbiosis were considerable. If only the direct emissions and resource use of the symbiosis had been considered, less than half of the total environmental impacts of the system would have been taken into account. When the results were compared with the counterfactual reference scenarios, the net environmental impacts of the symbiosis were smaller than those of the reference scenarios. The reduction in environmental impacts was mainly due to changes in the way energy was produced. However, the results are sensitive to the way the reference scenarios are defined.

LCA is a useful tool for assessing the overall environmental performance of industrial symbioses. It is recommended that in addition to the direct effects, the upstream impacts should be taken into account as well when assessing the environmental performance of industrial symbioses. Industrial symbiosis should be seen as part of the process of improving the environmental performance of a system. In some cases, it may be more efficient, from an environmental point of view, to focus on supply chain management instead.

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Tekijä(t)
Laura Sokka

Nimeke

Paikalliset systeemit – globaalit vaikutukset
Elinkaariarviointi teollisen symbioosin arvioinnissa

Tiivistelmä

Ihminen louhii ja siirtää erilaisia aineita ja materiaaleja maaperästä aiheuttaen samalla monia ympäristöongelmia, kuten ilmaston lämpenemistä, happamoitumista ja rehevöitymistä. Ongelmien tullessa monimutkaisemmiksi, on syntynyt tarve kokonaisvaltaisemmille menetelmille, jotka huomioivat saasteiden lähteen.

Teollinen ekologia on tieteenala, joka tarjoaa kokonaisvaltaisen viitekehyksen modernin teknologisen yhteiskunnan ja ympäristön välisen vuorovaikutuksen tutkimiseen. Teollisessa ekologiassa yhteiskunnan ajatellaan olevan osa luonnonympäristöä eikä erillinen siitä. Teollinen toiminta muodostaa luonnon systeemejä, joiden on toimittava biosfäärin asettamissa rajoissa. Keskeinen käsite teollisessa ekologiassa on teollinen symbioosi. Teollinen symbioosi tutkii materiaalin ja energian virtoja paikallisissa systeemeissä. Ihanteellisessa teollisessa symbioosissa symbioosin toimijat vaihtavat materiaaleja ja energiaa keskenään ja vähentävät siten päästöjä ja jätteitä. Yritykset nähdään kuluttajien ja tuottajien verkostona, joka muistuttaa luonnon ekosysteemiä.

Tämän tutkimuksen tavoitteena oli analysoida sellu- ja paperintuotantoon perustuvan teollisen symbioosin ympäristövaikutuksia huomioiden koko elinkaari. Elinkaariarviointi on menetelmä, jolla voidaan arvioida tietyn tuotteen, teknologian tai palvelun koko elinkaaren aikaiset ympäristövaikutukset. Natural Step -kestävyysperiaatteet muodostivat käsitteellisen viitekehyksen tutkimuskohteena olevan symbioosin ympäristövaikutusten arviointiin (osajulkaisu I). Tapaustutkimussymbioosin ympäristövaikutuksia verrattiin neljään teoreettiseen referenssiskenaarioon, joissa symbioosin toimijat toimivat erillään. Käytetyt tutkimusmenetelmät olivat niin sanottu prosessielinkaariarviointi (osajulkaisut II ja III) ja hybridielinkaariarviointi (osajulkaisu IV).

Tulokset osoittavat, että symbioosin käyttämien raaka-aineiden louhinnan ja prosessoinnin sekä energian tuotannon ympäristövaikutukset olivat huomattavia. Jos vain suorat päästöt ja raaka-aineiden kulutus olisi huomioitu, yli puolet symbioosin kokonaisympäristövaikutuksista olisi jäänyt huomioimatta. Kun tuloksia verrattiin referenssiskenaarioihin, voitiin todeta, että symbioosin nettoympäristövaikutukset olivat kaikissa vaikutusluokissa referenssiskenaarioita pienemmät. Tämä johtui pääasiassa energiantuotannosta. Tulokset ovat kuitenkin herkkiä sille, miten vertailuskenaariot määritellään.

LCA on hyödyllinen väline teollisten symbioosien kokonaisympäristövaikutusten arviointiin. Raaka-aineiden ja energian tuotannon ympäristövaikutukset tulisi huomioida, kun arvioidaan teollisen symbioosin kokonaisympäristövaikutuksia. Teollinen symbioosi tulisi nähdä yhtenä osana systeemin ympäristövaikutusten hallintaa. Joissakin tilanteissa saattaa olla ympäristön kannalta tehokkaampaa keskittyä hankintaketjun hallintaan teollisen symbioosin sijaan.

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• • • VTT PUBLICATIONS 768 LOCAL SYSTEMS, GLOBAL IMPACTS. USING LIFE CYCLE ASSESSMENT TO ANALYSE THE POTENTIAL AND...

Industrial ecology is a field of science that forms a comprehensive framework for studying the interactions between the modern technological society and the environment. A central concept of industrial ecology is industrial symbiosis (IS). Industrial symbiosis studies look at the physical flows of materials and energy in local industrial systems. In an ideal IS, waste material and energy are exchanged by the actors of the system, thereby reducing the consumption of virgin material and energy inputs and the generation of waste and emissions. Companies are seen as part of the chains of suppliers and consumers that resemble those of natural ecosystems.

The aim of this study is to analyse the environmental performance of an industrial symbiosis based on pulp and paper production, taking into account life cycle impacts as well. The research methods used are process-based life cycle assessment (LCA) and hybrid LCA. In order to assess whether industrial symbioses produce environmental benefits, the environmental performance of the case study system is compared to four counterfactual reference scenarios in which the actors of the symbiosis operate on their own. Moreover, the role of industrial symbioses in enhancing global environmental sustainability is discussed.

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