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Jouko Arvola

REDUCING INDUSTRIAL USE OF FOSSIL RAW MATERIALS

TECHNO-ECONOMIC ASSESSMENT OF RELEVANT CASES IN NORTHERN FINLAND

UNIVERSITY OF OULU,
FACULTY OF TECHNOLOGY,
DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT

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Abstract

Climate change and global warming are currently widely discussed topics, both of which potentially impact all the nations and industries. Carbon dioxide (CO_2) and other green house gases (GHG) are seen as a major challenge. This doctoral dissertation aims to conduct techno-economic calculations on the possibilities of reducing the industrial use of fossil raw materials in Northern Finland.

This doctoral dissertation analyses industrial CO_2 emissions from five complementary perspectives: identifying significant potential industrial plants, analysing the replacement of fossil raw materials with wood biomass, considering combining different industrial sectors, the potential of biogas as industrial raw material, and estimating the economic significance of moisture in wood fuel.

The study started by analysing all the relevant 262 regional environmental permits to find the significant industrial users of synthesis gas in the studied region. Processes used by each identified case were analysed carefully to identify the most potential change possibilities. Economic calculations were conducted for these cases using true production volumes. The aim was to reach solutions that were economically sound.

Five industrial sites were identified as potential cases for replacing raw materials of synthesis gas or hydrogen with renewable alternatives. These sites include the Rautaruukki steel mill, Eka Chemicals' hydrochloric acid plant, Kemira's formic acid plant, Kemira's hydrogen peroxide producing plant, and Talvivaara mining's hydrogen plant.

The main implications of this dissertation include providing tips for industrial managers, regional decision makers and legislators. Managers of companies with high energy consumption and/or high usage of fossil raw materials in their products can benefit from the results of this dissertation the most. Managers should conduct similar calculations, as in this study, by using exact figures relevant to their processes and raw materials. This doctoral dissertation also suggests finding new solutions for replacing fossil raw materials by combining two different industrial sectors, e.g. steel and chemical industries. Regional decision makers may utilise the calculations presented in this doctoral dissertation when developing regional strategies.

Keywords: biogas, biomass, climate change, CO_2 emissions, formic acid, industry, renewable raw materials, synthesis gas, techno-economic calculations

Arvola, Jouko, Fossiilisten raaka-aineiden teollisen käytön vähentäminen – relevanttien pohjoissuomalaisten tapausten teknistaloudellinen arviointi.
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Tiivistelmä

Ilmaston muutos ja globaali lämpeneminen ovat tällä hetkellä laajasti keskusteltuja aiheita, ja ne vaikuttavat kaikkiin maihin ja kaikkiin teollisuuden aloihin. Hiilidioksidi (CO_2) ja muut kasvihuonekaasut nähdään suurena haasteena. Tämä väitöskirja pyrkii teknistaloudellisten laskelmien avulla tutkimaan mahdollisuuksia vähentää fossiilisten raaka-aineiden käyttöä Pohjois-Suomen alueella.

Tämä väitöskirja analysoi teollisia CO_2-päästöjä viidestä toisiaan täydentävästä näkökulmasta: identifioimalla merkittäviä teollisia tuotantolaitoksia, analysoimalla fossiilisten raaka-aineiden korvaamista puubiomassalla, tutkimalla erilaisten teollisten tuotantolaitosten yhdistämistä, tutkimalla biokaasun käyttöä mahdollisena teollisuuden raaka-aineena ja arvioimalla kosteuden taloudellista merkitystä puupolttoaineessa.

Tutkimus alkoi analysoimalla kaikki alueen identifioidut 262 ympäristölupaa, jotta merkittävät synteesikaasun käyttäjät tulisivat esille. Jokaisen löydetyn tapauksen tuotantoprosessit analysoitiin huolellisesti, jotta potentiaalisimmat muutosmahdollisuudet huomioitaisiin. Teknistaloudellisia laskelmia tehtiin näille tapauksille käyttämällä todellisia tuotantolukuja. Tarkoituksena oli löytää taloudellisesti kannattavia vaihtoehtoja.

Viisi teollista tuotantolaitosta identifioitiin tapauksiksi, joissa synteesikaasun tai vedyn raaka-aine voitaisiin korvata uusiutuvilla raaka-ainevaihtoehdoilla. Nämä tuotantolaitokset olivat Rautaruukin terästehdas, Eka Chemicalsin kloorivetyhapon tuotantolaitos, Kemiran muurahaishappotehdas, Kemiran vetyperoksiditehdas ja Talvivaaran kaivoksen vedyn tuotantolaitos.

Tärkeimmät implikaatiot tästä väitöskirjatyöstä sisältävät pohdittavia ajatuksia teollisille toimijoille, alueellisille päätösten tekijöille ja lainsäätäjille. Korkean energian kulutuksen ja/tai suurten fossiilisten raaka-ainekäyttöjen yhtiöissä päätöksentekijät voivat hyödyntää parhaiten tämän väitöskirjan tuloksia. Päätöksentekijät voisivat käyttää esimerkkeinä tämän väitöskirjan laskelmia tehdessään omia analyyseja, jolloin heidän tulisi käyttää tarkkoja lukuja yritystensä prosesseista ja raaka-ainekäytöistä. Tämä väitöskirja ehdottaa myös etsimään uusia ratkaisuja fossiilisten raaka-aineiden korvaamisessa yhdistämällä tuotannollisesti erilaisia teollisia sektoreita esimerkiksi teräksen ja kemian tuotteiden valmistuksen. Alueelliset päätösten tekijät voivat hyödyntää väitöskirjassa esitettyjä laskelmia alueellisten strategioiden kehitystyössä.

Asiasanat: biokaasu, biomassa, CO_2 -päästöt, ilmaston muutos, muurahaishappo, synteesikaasu, teknis-taloudelliset laskelmat, teollisuus, uusiutuvat raaka-aineet

Acknowledgements

My extensive industrial career was put on hold three years ago when I took the opportunity of joining the Department of Industrial Engineering and Management (DIEM) at the University of Oulu. The university provided me with new challenges in continuing studying similar issues my previous career supports, renewable energy and developing new. DIEM has enabled me to work in an inspiring environment and cooperate with multiple bodies and projects. This interaction has enabled enhancing my views and know-how. Working on my doctoral dissertation and the related journal articles has hopefully brought a tiny addition to the discussion in the scientific community.

I would like to thank my supervisors Professor Pekka Kess and Dr Pekka Belt for providing invaluable advice for completing my work. I would also like to thank Dr Janne Härkönen and Dr Matti Möttönen for their intensive support during the dissertation process.

During the past two years I have written five publications in cooperation with my colleagues. I would like to thank my co-authors Dr Pekka Belt, Dr Janne Härkönen, Dr Matti Möttönen, Dr Matti Muhos, Prof. Pekka Kess, Prof. Harri Haapasalo, Dr Pekka Tervonen, and Ms Ritva Imppola for their participation. I have benefitted of their know-how and intensive discussions, speeding up my own learning process.

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Oulu, November 2011 Jouko Arvola

List of abbreviations and definitions

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CH_3OH	Methanol
CH_3OOCH	Methyl formate
C_2H_5OH	Ethanol
C_2H_5OOCH	Ethyl formate
CH_3COOH	Acetic acid
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CCS	Carbon Capture and Storage
€	Euro
EC	European Commission
EF	Ecological Footprint
EU	European Union
EU ETS	European Union Emission Trading System
ETS	Emission Trading System
EU 15 steel	Steel produced in first fifteen EU countries
FA	Formic Acid
Fuel CO_2 price	Fuel specific emissions cost for CO_2 release
GHG	Green House Gasses
Gt	Gigatonnes
$GtCO_2e$	Gigatonnes carbon dioxide equivalent
GTK	Geological survey of Finland
ΔH_{vap}	Enthalpy of vaporisation
ha	Hectare
H_2	Hydrogen
HCOOH	Formic acid
HFO	Heavy Fuel Oil
H_2O	Water
H_2S	Hydrogen sulphide
H_2O_2	Hydrogen peroxide
IPCC	Intergovernmental Panel on Climate Change
ktoe	Kilotonne oil equivalent

LHV	Lower Heating Value
LHV_A	Lower Heating Value on arrival
LHV_D	Lower Heating Value for dry wood
M€	Million €
MJ	Megajoule
MWh	Megawatt hour
N_2	Nitrogen
NG	Natural Gas
NH_2CONH_2	Urea
NH_3	Ammonia
Nm^3	Normal cubic meter
O_2	Oxygen
ppm	parts per million
synthesis gas	gas mixture containing carbon monoxide and hydrogen
RCG	Reed Canary Grass
RQ	Research Question
t	Tonne
TWh	Terawatt hour
USA	United States of America
VTT	Technical research centre of Finland
w-%	Weight percentage

List of original publications

This dissertation is based on the following publications:

I Arvola J, Belt P, Harkönen J & Möttönen M (2011) Replacing fossil raw materials by using renewable sources in Northern Finland. 2nd International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS2), 19–21 June, 2011, Nisyros – Greece.

II Arvola J, Muhos M, Belt P & Kess P (2011) Renewable energy in chemical industry – the case of formic acid production. International Journal of Sustainable Economy 3(4): 381–394.

III Arvola J, Härkönen J, Möttönen M, Tervonen P & Haapasalo H (2011) Combining steel and chemical production to reduce CO_2 emissions. Low Carbon Economy 2(3): 115–122.

IV Arvola J, Belt P, Härkönen J, Kess P & Imppola R (2012) Biogas as an option for industrial applications. International Journal of Sustainable Economy 4(1): 71–88. In press.

V Arvola J, Belt P, Härkönen J, Möttönen M & Kess P (2011) Economic impact of moisture in wood-based bio-fuels. TIIM 2011 Conference, June 28–30, Oulu, Finland.

The author of this dissertation is the primary author of all original publications. The researcher has been responsible for formulating the research problems, collecting the theoretical base, formulating the research questions, coordinating the collection of empirical material, analysing the material and drawing conclusions. The researcher is also the primary author of all the five articles. The role of co-authors includes reviewing and commenting the article manuscripts of the first author.

Contents

1 Introduction

1.1 Background and research environment

This doctoral dissertation conducts techno-economic calculations on the possibilities of reducing the industrial use of fossil raw materials in Northern Finland. More specifically, this study studies significant industrial synthesis gas users in the geographical areas of Northern Ostrobothnia and Kainuu. Climate change and global warming are currently widely discussed topics, both having the potential of impacting all nations and industries. Carbon dioxide (CO_2) and other green house gases (GHG) are seen as a major challenge (United Nations 1997, Schmalensee *et al.* 1998, White & Sulkowski 2010). Use of carbon-based raw materials is largely the origin behind CO_2 increase in the atmosphere. The global atmospheric concentration of CO_2 has increased from a preindustrial value of about 280 ppm to 379 ppm and is still increasing (IPCC 2008).

Climate change and global warming take place due to increase in carbon dioxide concentration in the atmosphere. The changes are irreversible and directly related to the magnitude of atmospheric CO_2 concentration, i.e. more atmospheric CO_2 results in a bigger impact on the climate (Cox *et al.* 2000, Houghton *et al.* 2001, Solomon *et al.* 2009).

In general, there are various means for reducing the formation of GHG gases. Improving energy efficiency is one with the most potential (e.g. Greening *et al.* 2000, Dincer 2002, Hoffert *et al.* 2002). Carbon intensity of fuels is in direct proportion to CO_2 emissions (Canadell *et al.* 2007, Pielke *et al.* 2008). Nuclear energy is also an avenue for avoiding CO_2 (e.g. Van der Zwaan 2008) while using renewable energy is another one (e.g. Hoffert *et al.* 2002, McKendry 2002).

In the industry, the means for reducing the formation of GHG gases are mostly the same as above. However, there are many noteworthy field specific technologies, such as carbon capture and storage (CCS), that are especially suitable for industries with gases with high CO_2 concentrations (e.g. Pacala & Socolow 2004, Haszeldine 2009). In addition, industrial emission mitigation options, aside from energy efficiency improvement, include considering new processes, shifting towards using low carbon fuels, and applying waste fuels, among others (e.g. Worrell *et al.* 2001).

In Europe, the European Union has established an emissions trading scheme (EU ETS) for reducing CO_2 emissions. This EU ETS is designed to be a tool for combating climate change and for reducing industrial greenhouse gas emissions cost-effectively. Each company must surrender enough allowances annually to cover all its emissions; otherwise heavy fines are imposed. Should a company reduce its emissions, it may keep the spare allowances to cover its future needs or it may sell them to another company that is short of allowances. The total number of allowances is reduced over time so that total emissions fall gradually. In 2020 emissions will be 21% lower than in 2005. (European Commission 2010).

Regional considerations and local strategies are among the important topics widely discussed in Europe when the means for improving the economy and employment are considered. Regions are coming up with their own development strategies for different matters and they are widely discussing topics on reacting to climate change and going green. For example, in Finland different regions have made local strategies based on the national energy strategy (Council of Oulu region 2007, Finnish Government 2008). Literature also gives examples of sustainability indicators developed for local-level governance (e.g. Rydin *et al.* 2003). Domac *et al.* (2005) study the socio-economic drivers for implementing greener solutions, and view regional development in the sense of job creation, income improvement and local environment as equally important as reducing carbon emissions securing energy supply at a national level. Similarly, Elghali *et al.* (2007) agree that in reducing GHG emissions, social and economic factors play a key role.

Moreno & Lopez (2008) and Wei *et al.* (2010) have studied the impact of renewable energy on employment and concluded positive effects. Smyth *et al.* (2010) have analysed whether grass based biomethane is an economically viable biofuel for farmers and consumers. Pahkala *et al.* (2008) have studied grass farming for energy production. Scott et. al. (2007) have studied how biomass could be utilised for producing chemical products, and Weiland (2003) has studied the production of energy via biogas from energy crops and waste.

Industries have considered means for reducing green house gas emissions. Corma *et al.* (2007) and Hayes *et al.* (2006) have analysed chemical production directly from biomass. Kamm (2007) and Van der Drift & Boerrigter (2006) have studied chemicals production via biomass gasification. However, these studies emphasise chemistry and production technologies, leaving room for tangible techno-economic considerations.

Previous studies have not conducted techno-economic analyses on large industrial cases. They also have not fully covered replacing fossil raw materials with renewable ones by thoroughly analysing industrial processes and their energy use for reducing CO_2 emissions. For example, the literature has not considered in detail formic acid processes by using wood for heat production and for producing synthesis gas. The literature has not adequately addressed the economies of scale for renewable raw material selection. The literature has a tendency of presenting industry sector specific analyses and the cross-sector considerations are lacking. However, discussion on climate change and the actions for reacting to it open new, even radical, opportunities for cross-sector thinking. With regards to bioenergy production and use, the literature emphasises decentralised production and decentralised use (e.g. Hiremath *et al.* 2009). Large scale industrial processes would enable the large scale use of renewable raw materials. These deficiencies described above provide justification for this doctoral dissertation.

1.2 Objectives and scope

The main motive for this research arises from the fact that regardless of previous studies, reducing the industrial use of fossil raw materials is still an acute challenge. Clearly there is a need for studying tangible means of fighting climate change. Europe has a strong trend towards using renewable energy solutions, but its regions still need to consider climate change and actions for combating it, when making their strategies. These considerations should see the potential opportunities as well as the threats of the green trend.

This doctoral dissertation does not aim to judge whether or not the actions taken by legislators or other authorities are right, or whether global climate is truly changing or merely fluctuating naturally. Instead, this research aims to analyse changes in the business environment, including understanding the actions by authorities as existing facts and conducts economic calculations based on true industrial cases. This dissertation analyses the feasibility of changing industrial processes according to existing reality. It does not, however, analyse whether the presented alternative solutions are truly environmentally better than the previous ones.

The research problem of this doctoral dissertation is formulated as below:

> *Are there technical and economic possibilities for large industrial companies that use synthesis gas in Northern Finland, to develop their processes in order to react to changes in the business environment caused by actions of authorities trying to curb climate change? Is it feasible for industrial*

companies to change their raw material sources in order to react to changes in the surrounding reality?

The purpose of this dissertation is to examine whether or not it is possible to reduce the industrial use of fossil raw materials in companies that utilise synthesis gas in Northern Finland. This dissertation analyses industrial cases by using techno-economic calculations, attempting to clarify whether it is economically feasible to reduce the use of fossil raw materials in large industrial sites that utilise synthesis gas.

This problem is studied from four complementary perspectives: analysing the replacement of fossil raw materials by wood biomass, estimating the economic significance of moisture in wood fuel, considering combining different industrial sectors and the potential of biogas as industrial raw material (Table 1).

Table 1. Research questions.

RQ#	Research question
RQ1	Is it technically and economically feasible to replace fossil raw materials with wood biomass in the chemical industry's formic acid processes?
RQ1.1	What is the economic significance of wood chip moisture?
RQ2	Is it technically and economically feasible to combine steel manufacturing and chemical production when considering one's by-product as other one's raw material?
RQ3	Is biogas a technically and economically feasible alternative as raw material for industrial synthesis gas users?

The research problem is addressed with five scientific peer-reviewed articles. The first article identifies significant potential industrial plants that use synthesis gas in Northern Finland. Articles II, III, and IV answer the research questions 1, 2, and 3 respectively, providing partial solutions to the research problem. The role of Article V is to complement Article II by analysing the economic significance of wood chip moisture. The contributions of these articles are combined in this compilation dissertation.

Figure 1 illustrates the positioning of the five research articles. The first article identifies potential cases to be studied. The second article analyses the potential of using renewable energy in the chemical industry, particularly concentrating on the case of formic acid production. The third article takes a novel approach by considering possibilities of combining steel and chemical production to reduce CO_2 emissions. The fourth article studies the potential of utilising biogas as an option for industrial applications by analysing three different alternatives. The fifth article considers the quality of bio-fuels by estimating the economic impact of moisture in wood chips; hence, supporting Article II. All of these articles and this compilation have been realised from a perspective that combines technical, economic and social goals.

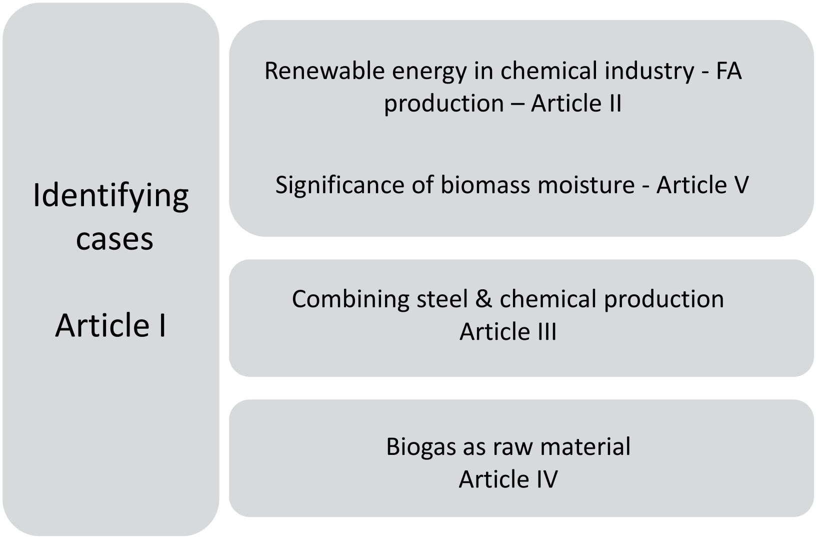

Fig. 1. Relationship between the research articles.

1.2.1 Identifying cases to be studied

Article I analysed 262 regional environmental permits in Northern Finland in order to find significant industrial gas users and to examine whether or not the raw materials are feasible to be produced by renewable sources.

Five cases were identified as having the most potential to be used for further analyses. The volumes of the five identified cases are large enough to justify the consideration of sustainable alternatives. These five cases include 1) replacing oil in formic acid and hydrogen peroxide production by using wood biomass for synthesis gas production (Kemira I), 2) replacing oil in formic acid and hydrogen peroxide production by using biogas from a landfill (Kemira II), 3) replacing oil in formic acid and hydrogen peroxide production by using biogas from anaerobic fermentation (Kemira III), 4) replacing propane in hydrogen production by using methane, biogas obtained via anaerobic fermentation (Talvivaara) and 5) utilising furnace gases for industrial purposes (Rautaruukki). In cases 1–3, replacing peat in steam production by using wood biomass was also analysed. Eka Chemicals was identified to have high enough volumes, but their processes do not produce carbon dioxide. Therefore analysing Eka chemicals further was left outside the scope of this study. Table 2 provides numerical data on the five identified cases.

Table 2. Numerical data on the five identified cases.

Kemira I	Current solution	Alternative solution Wood biomass gasification
Input	HFO: 37 000 t	CO, H_2: 100 000 000 Nm^3
Requires		wood biomass
Output	FA & H_2O_2: 160 000 t	FA & H_2O_2: 160 000 t

Kemira II	Current solution	Alternative solution Landfill biogas
Input	HFO: 37 000 t	CH_4: 4 000 000 Nm^3
Requires		landfill gas
Output	FA & H_2O_2: 160 000 t	FA & H_2O_2: 9 700 t

Kemira III	Current solution	Alternative solution Biogas from anaerobic fermentation
Input	HFO: 37 000 t	CH_4: 33 300 000 Nm^3
Requires		16 700 ha farm land
Output	FA & H_2O_2: 160 000 t	FA & H_2O_2: 160 000 t

Talvivaara	Current solution	Alternative solution Methane from anaerobic fermentation
Input	propane: 15 000 t	CH_4: 19 000 000 Nm^3
Requires		9 500 ha farm land
Output	H_2: 4 000 t	H_2: 4 000 t

Rautaruukki	Current solution	Alternative solution Industrial use of furnace gases
Input	pure CO: 578 000 000 Nm^3	pure CO: 578 000 000 Nm^3
Requires		Replacement energy
Output	Energy	Chemicals

Article I identified the following significant alternatives for producing synthesis gas: *biomass gasification*, *landfill biogas*, biogas via *anaerobic fermentation*, and the use of *steel mill gas* which is an industrial by-product.

1.3 Research process

Researchers face epistemological, ontological and ethical questions, when approaching scientific research from a philosophical viewpoint, i.e., How can one believe and know of reality based on scientific research?; How is scientific knowledge obtained and when is this knowledge scientific?; When does the researcher abuse his research object or act unethically against scientific community?. (Lancaster 2005).

Ontology can be understood as a reality where studied phenomena are understood to exist and how they relate to this reality. Ontological pre-conceptions on the nature of studied issues are typical for scientific research. Ontology determines whether the reality is objective or subjective. Ontology is seen to influence the choice of theory and concepts. (Anttila 2005, Harisalo 2008). Epistemology, on the other hand, is concerned with what is regarded as appropriate knowledge about the social world. A vital aspect is a question over whether a natural science model of the research process is suitable for studying the social world. (Bryman & Bell 2007).

Figure 2 illustrates epistemological and ontological starting points for this research.

Fig. 2. Epistemological and ontological starting points.

Epistemology can be roughly divided into positivism and interpretivism (Saunders 2007). This research is closer to positivism than interpretivsm. According to positivism, only phenomena and knowledge that can be assured through the senses can be considered as knowledge. In positivism research, mainly deductive approaches are followed and the role of the researcher is to remain distant and objective. The aim is to assure repeatability and the research methods are to be selected accordingly. (Saunders 2007).

Ontology can be roughly divided into objectivism and subjectivism. This research is closer to objectivism than subjectivism. Objectivism is an ontological position implying that research is based on facts rather than subjective analysis. (Saunders 2007, Bryman & Bell 2007).

This dissertation analyses industrial cases by using techno-economic calculations, attempting to clarify whether industrial CO_2 emissions can be simultaneously reduced. This study covers the geographical areas of Northern Ostrobothnia and Kainuu. The cases include analysing the replacement of fossil raw materials with renewable alternatives. The study was started by analysing all the relevant 262 regional environmental permits to find the significant industrial gas users in the studied region. The Finnish environmental legislation has defined the content required for environmental permits (Finnish Government 2000). Consequently, environmental permits contain relevant information that can be utilised to analyse industrial processes, volumes and emissions. Over two hundred of these permits cover farming or similar activities. Five industrial scale synthesis gas users were identified among the analysed industrial permits. The researcher thoroughly analyse all of these industrial actors and their processes. These five industrial sites were identified as potential cases for replacing the raw material of synthesis gas or hydrogen with renewable alternatives. According to the environmental permits, these five sites cover all synthesis gas usage in the studied region. These sites include the Rautaruukki steel mill, Eka Chemicals' hydrochloric acid plant, Kemira's formic acid plant, Kemira's hydrogen peroxide producing plant, and Talvivaara mining's hydrogen plant.

Article I concentrates on finding cases that have high enough volumes to consider replacing current raw materials with renewable ones. Article I also covers analysing technical aspects of current industrial processes to determine whether a transition towards reducing CO_2 emissions is technically possible. Technical aspects were analysed through the study of detailed process descriptions in environmental permits. Each studied case has been carefully analysed to understand whether there are significant means of reducing CO_2 emissions. Process details including inputs, outputs, raw materials and emissions were thoroughly analysed. Special emphasis was given on the analysis of those process phases that can be influenced. Literature was utilised to identify potential ways to reduce CO_2 emissions. The technical applicability of these identified potential means for CO_2 reduction was reviewed thoroughly for each of the five industrial cases.

Articles II–IV concentrate on analysing the economic feasibility of transition towards environmentally sounder solutions in the identified industrial cases. Processes for each case were analysed carefully to identify most potential change possibilities. Economic calculations were conducted for these identified changes using true production volumes. The criterion was to reach solutions that were economically sound and would simultaneously reduce CO_2 emissions. Prices of raw materials required for both current and more sustainable solutions were obtained from Statistics Finland. Investment costs for required equipment were gathered from suppliers.

Moisture is an important quality criterion for biomass use. Article V analyses the economic impact of moisture in wood-based bio-fuels in Finland. The article utilises literature reviews and expert interviews to obtain adequate understanding on the impact of moisture in wood-based bio-fuels. Economic calculations were conducted to clarify the impact of moisture in wood chips in Finland.

2 Theoretical foundation / literature review

2.1 Global green house gas emissions

It is a commonly accepted fact that the world will face further climate changes, which will lead to adverse impacts in many areas (Vörösmarty *et al.* 2000, Thomas *et al.* 2004, Stern 2007). Global temperatures will continue to rise having severe environmental impacts. Urgent actions are required to reduce atmospheric green house gases (GHG). Stabilisation of GHG concentration in the atmosphere requires that annual emissions are brought down to the level equal to the Earth's natural capacity to absorb greenhouse gases from the atmosphere (Grace 2001, Corfee-Morlot & Höhne 2003). Carbon emissions are directly proportional to energy consumption. In order to reach the required stability, global emissions should be drastically cut to below 5 $GtCO_2e$, which is approx. 20% of the current emission levels (Stern 2007). Stabilisation cannot be achieved without global actions to reduce emissions. (Aldy *et al.* 2003, Enkvist *et al.* 2007, Miles & Kapos 2008).

The annual GHG emissions in 2004 were 38 Gt as CO_2-eq and the top three sources of greenhouse gases caused by human activities included burning of fossil fuels CO_2, deforestation and land use CO_2, CO_2 and many more (Steinfeld *et al.* 2006, IPCC 2008).

2.2 Reducing CO_2 emissions

The global discussion on climate change and the effects of carbon dioxide emissions derived from fossil raw materials has led to new environmental thinking and legislation (e.g. United Nations 1997, Schmalensee *et al.* 1998, White & Sulkowski 2010). The use of renewable energy instead of fossil raw materials is currently seen as an essential way to reduce green house gas emissions (United Nations 1997, Hoffert *et al.* 2002, IPCC 2008). The Kyoto Protocol treaty that became effective in 2005 was negotiated to reduce the global greenhouse gas emissions in a globally coordinated manner (United Nations 1997). The main factors guiding the reduction of emissions include legislation, emissions trading, tariffs, investment supports, and many more (e.g. Raupach *et al.* 2007, Fouquet & Johansson 2008, Kara *et al.* 2008).

"An energy policy for Europe" acts as a guideline for the European Union countries in dealing with national energy policies (Commission of the European Communities 2007). The main issue is EU being committed to reducing its overall emissions, calculated as CO_2, to at least 20% below the 1990 levels by 2020. There is also a target of 20% for renewable energy by 2020. Emissions from transport, housing, agriculture and waste will also be cut by 10% from the 2005 levels by 2020.

The industry has potential for reducing CO_2 emissions. This potential should be considered by analysing existing processes on a case-by-case basis. The uses of fossil fuels in the industry range from process heat to reducing agents or hydrocarbon feedstocks (e.g. Unander *et al.* 1999, Worrell *et al.* 2000, Einstein *et al.* 2001). Cleaner alternatives typically include natural gas, biomass and electricity if produced in a sustainable manner. The use of coal is to be reduced as well. However, in iron and steel production, coal use will be continued in conjunction with carbon capture and storage (CCS) because the alternatives are scarce. (Teir *et al*. 2011).

According to the IPCC (2008), the most potential means of reducing CO_2 in the industry include more efficient use of electrical equipment, heat and power recovery, material recycling and substitution and control of non-CO_2 gas emissions. In addition, there is a wide range of process-specific technologies for different industrial sectors, including advanced energy efficiency and CCS for cement, ammonia and iron manufacture (IPCC 2007, Stern 2007).

Ecological footprint (EF) is an indicator also used for local development It is initially developed for measuring national consumption. The EF has attracted interest in its application at regional and local levels (Wackernagel 1998, Lenzen & Murray 2001, Wiedmann & Minx 2007). Different indicators involve different types of analysis, such as monitoring the state of the environment, trend analysis, benchmarking, reporting in a decision-making hierarchy, impact assessments and evaluations (Aall & Norland 2005). According to Kautto *et al.* (2011) more research on regional and local levels is needed to clarify the lower level impacts of greener solutions. However, even though regional development has been studied from different perspectives, more tangible solutions are required to complement the literature.

2.2.1 Emissions trading and its influence on energy use

EU directive (2003/87/EC) has set principles for greenhouse gas related emissions trading since 2005, covering electricity production, heat production, oil refineries, coking plants, steel production, mineral industries and pulp and paper industries. The basic principle of emissions trading is that companies must cover their CO_2 emissions by emission rights. Emission rights can be bought and sold based on daily market price. Companies have to acknowledge this price in their daily operations and strategic planning. (Nykänen *et al.* 2006). In Finland, emission trading covered about 160 companies and some 570 plants (National Audit Office of Finland 2009)

The emissions trading is controlled by the governmental Energy Market Authority. When energy is produced from fuel containing carbon, the emission trading rules must be followed. In emission trading, the CO_2 cost for renewable energy, such as biomass, is zero as it is considered a part of the natural carbon cycle. An incentive is, therefore, provided for considering changing from using fossil energy to using renewable energy. The change to renewable energy is economically motivated when the CO_2 cost and fuel price are greater than the cost of renewable energy. Potential excess CO_2 emission allowances can be sold in the market should the producer have greater emission permits than actually needed (see Energy Market Authority 2010, p. Emissions trading).

Graichen *et al.* (2008) have analysed that the EU ETS scheme has had a minor negative impact on the competitive position of some industries in Germany, but in general has had no major negative influence. In Finland, Kara *et al.* (2008) have found that the emissions trading system increase the annual average electricity price by some $0.74\ \mathrm{EUR\ MW\ h^{-1}}$ for every $1\ €\ /\ \mathrm{tonne\ CO_2}$ in the Nordic countries. This price increase is seen to have an impact on the competitiveness of Finnish industries, as for example the metal industry relies almost completely on electricity bought from the market. The main competitors of the metal industry are mainly located outside the EU area and are not influenced by the emissions trading system. However, Demailly and Quirion (2008) argue that competitiveness losses are small for the steel industry when considering the production and profitability dimensions of competitiveness. Hidalgo *et al.* (2005) argue that the implementation of the EU15 emission permit market would increase the cost of the EU15-made steel and that would translate into an emission and production leakage from the EU15 to the rest of the world, mainly to China. On the other hand, the Finnish pulp and paper industry can alleviate the negative effects of the EU emissions trading as they own most of their electricity and heat supply. The EU emissions trading of carbon dioxide is seen to bring considerable competitive advantage to carbon-free energy production forms. (Kara *et al.* 2008).

Frondel *et al.* (2010) argue that German renewable energy policy and, in particular their feed-in tariff scheme, has failed to harness the market incentives needed to ensure a viable and cost-effective introduction of renewable energies into the country's energy portfolio. In Finland, renewable energies are promoted mainly via the emissions trading system, energy taxes, different investment supports and feed-in-tariffs for electricity production via wind, wood biomass and biogas (Ministry of employment and the economy 2010).

Emissions trading costs are determined as for any other commodity derivatives in commodities exchanges; thus they are dependent on supply and demand (European Parliament 2003). Since the commencement of the ETS in 2005, the market prices as monthly averages have varied between 4–28 €/ t CO_2 (European Climate Exchange 2010). The average price for August 2010 was approx. 15 €/ t CO_2 (Nord Pool 2010). The prices are forecasted to develop to 13–25 € t/ CO_2 by 2012 and to 30–48 € / t CO_2 by 2020 (Kossoy & Ambrosi 2010, Thomson Reuters 2010). However, there are many factors that influence the markets (e.g. Tietenberg 2010, Convery & Redmond 2007) and forecasting exact market prices is difficult.

2.3 Reducing CO_2 emissions in Finnish industry by using renewable alternatives

Global carbon dioxide emissions in 2008 were approximately 30 000 million tonnes. 43% of these CO_2 emissions originated from coal, 37% from oil and 20% from gas (International energy agency 2010).

In Finland, greenhouse gas emissions were approx. 66 million tonnes in 2009 (see Figure 3). Emissions originated as follows: 80% from the energy sector, 9% from agriculture, 8% from industrial processes, and 3% from waste. 13% of the energy sector emissions originated from the industry's own energy production. Emissions from industrial processes are distributed as follows: 37% from the metal industry, 28% from the chemical industry, 17% from the minerals industry and 18% from the use of fluoride gases. Industrial CO_2 emissions totalled some 12 million tonne equivalents: 5 million tonnes from industrial processes and 7 million tonnes from industrial energy consumption of self-produced energy (Statistics Finland 2011). These figures exclude energy purchased from external sources. Figure 4 illustrates the distribution of greenhouse gases from industrial processes in Finland.

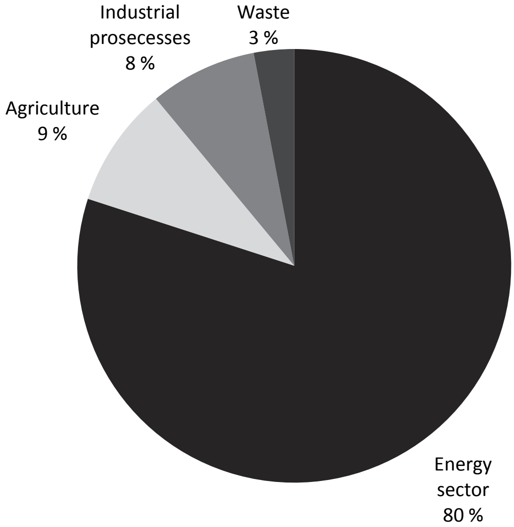

Fig. 3. Finnish greenhouse gas emissions in 2009.

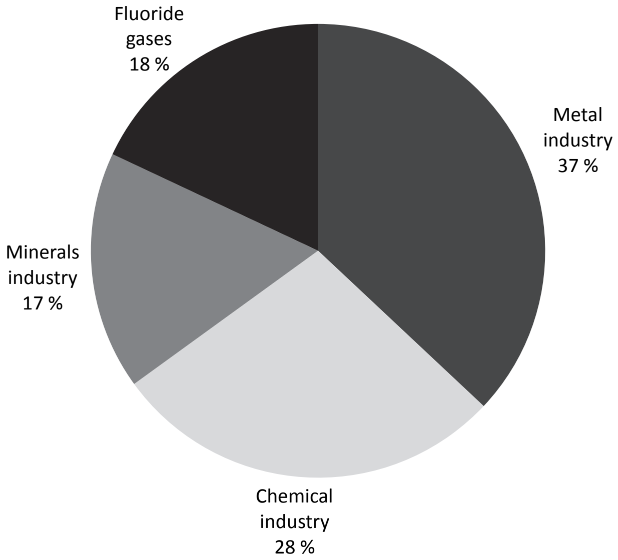

Fig. 4. Greenhouse gases from industrial processes in Finland.

When considering energy use only, the distribution of consumption of final energy in 2009 in Finland was: industry 47%, housing 23%, transport 17% and others 13%. Energy sources included: oil 25%, nuclear 18%, coal 12%, natural gas 10%, peat 5%, renewables 23%, and others 7% (Statistics Finland 2010).

Greenhouse gas emissions in Northern Ostrobotnia and Kainuu during 2007–2009 totalled to some 9.6 million tonnes (Bionova Engineering 2009, Monni 2010). Energy emissions, including trafic were 4 million CO_2-eq tonnes, industrial processes 4.7 million CO_2-eq tonnes, 95% of which originate from Rautaruukki steel mill. Farming was responsible for 0.8 and waste 0.1 million CO_2-eq tonnes.

The goal of the Finnish national long-term climate and energy strategy 2008 (Finnish Government 2008) is stricter than in Europe in general. The share of renewable energy out of total energy consumption should be increased to 38% by 2020. Renewable energy sources, such as wood biomass, field biomass, biogas production, waste incineration, ground heat, solar energy and wind power are widely available in Finland and have great potential to be used as replacement for non-renewable energy sources (Council of Oulu Region 2007). Kurkela (2002), Kurkela (2009) and Helynen (2008) have presented concrete studies on the use of biomass in Finland. Internationally, authors such as Huber *et al.* (2006) have made economic calculations on the use of biomass.

Finland has committed itself to increasing the proportion of renewable energy in energy production as required by the European Parliament (directive 2009/28/EC). The country is required to increase the proportion of renewable energy to 38% by 2020. The goal is to increase the annual share of renewable energy by 38 TWh by 2020. Finland is aiming to fill the requirements mainly by using wood biomass. 25 TWh of this energy is planned to originate from forest chips, 7 TWh from biofuels in traffic, and 2 TWh from pellets. The Finnish government utilises subsidies as a guiding mechanism towards renewable use. The incentives are directed to wood chipping, using wood for electricity production in existing power plants and investment supports for new plants. (Ministry of employment and the economy 2010). The emissions trading is an additional motivation towards using renewable sources (European parliament 2003). With emission trading costs of 20 €/tonne CO_2, wood becomes a viable alternative for fossil fuels. Consequently, wood fuel use will increase in energy plants that have suitable boiler technology. (Ranta *et al.* 2007).

Biomass is a renewable source of energy for producing steam, fuel and chemicals when the bio-energy chain is such that there is climate neutrality and efficient recycling of nutrients (Reijnders 2006). Nature produces some 200 billion tons of biomass through photosynthesis per year, out of which only 3–4 percent is utilised by humans (Jenck *et al.* 2004). The traditional use of wood as fuel is not considered sustainable as only the heat component is utilised. Co-generation of electricity and heat is preferred as the full potential of raw material is better exploited this way. Agricultural and forest residues and solid waste can also be used for producing transportation fuels. (Goldemberg & Teixeira Coelho 2004). Biomass has potential significance in the future global energy supply, regardless of whether it is considered from the viewpoint of climate change. However, the expanding bio-energy sector can potentially interact with other land uses, such as food production, biodiversity and soil and nature conservation. (Berndes *et al.* 2003).

2.4 Significant industrial processes in Northern Finland

The significant industrial processes in the geographical area, that are given focus by this doctoral dissertation include Kemira's formic acid production in Oulu, Rautaruukki's steel production in Raahe and Talvivaara's nickel mine in Sotkamo.

2.4.1 Formic acid production

Formic acid (FA) production is a significant industrial process in Northern Finland. Kemira Oyj is the leading producer of organic acids in chosen customer segments and the second biggest producer of formic acid in the world with a capacity over 100 000 t/a (Kemira Oyj 2006, Kemira Oyj 2008).

Formic acid production processes can be classified into four groups: methyl formate hydrolysis, oxidation of hydrocarbons, hydrolysis of formamide and preparation of formic acid from formates. Hydrolysis of methyl formate is the main method used for the production of formic acid worldwide and also used by Kemira (Reutemann & Kieczka 2000).

Worldwide capacity and production figures for formic acid are estimated at 620 thousand t/a and 450 thousand t/a, respectively, in 2004 with an annual demand growth of 2–3%. This converts into a turnover of approximately 300 million €/a. (Yali 2006). Formic acid is used for adjusting the pH when dyeing natural and synthetic fibres in the manufacture of pharmaceuticals and in crop-protection agents. Formic acid also plays an important role in the coagulation of rubber latex. In Europe, formic acid is commonly used as a silage aid (Reutemann & Kieczka 2000).

Carbon dioxide emissions in formic acid process that use hydrolysis of methyl formate include two main sources: steam production and production of synthesis gas. Raw materials for global synthesis gas production by partial oxidation include: coal 55%, petroleum 33%, and natural gas, pet-coke, biomass, & wastes 12% (Childress Associates 2007). However, steam reforming of natural gas is the most commonly used process for producing hydrogen in large quantities (Basye & Swaminathan 1997). Total synthesis gas production is 6000 PJ/a corresponding to approx. 2% of the world energy consumption. The main applications include: ammonia production 53%, oil refineries 23%, methanol production 11%, gas to liquids production 8%, and others 5% (Van der Drift & Boerrigter 2006).

After use, formic acid typically decomposes into CO_2 and water (Stickland 1929, Barham & Clark 1951, Weinstock 1969, Akiya & Savage 1998). The CO_2 is gradually released to the atmosphere when using FA, or other carbon dioxide releasing products, are not included in the legislative emission calculations (Finnish Government 2011).

Figure 5 illustrates Kemira's formic acid production process based on the environmental permits granted by The Environmental Centre of Northern Ostrobothnia (2007a, 2007b). The illustration presents the annual feed energy as MWh's and oil as tonnes for synthesis gas production, for the purpose of formic acid production (e.g. Arvola *et al.* 2011). The main net reaction of formic acid production is:

$$CO + H_2O \rightarrow HCOOH. \qquad (1)$$

During FA production, the main energy is consumed while preparing CO, compressing gas & pumping liquids, and above all in distillations. Rough consumption figures are: for steam 7.75 t/produced tonne of end product, and for electricity 130 kWh/t (Hydrocarbon Processing 1983). Consequently, the use of electricity is less significant, compared to steam and gas.

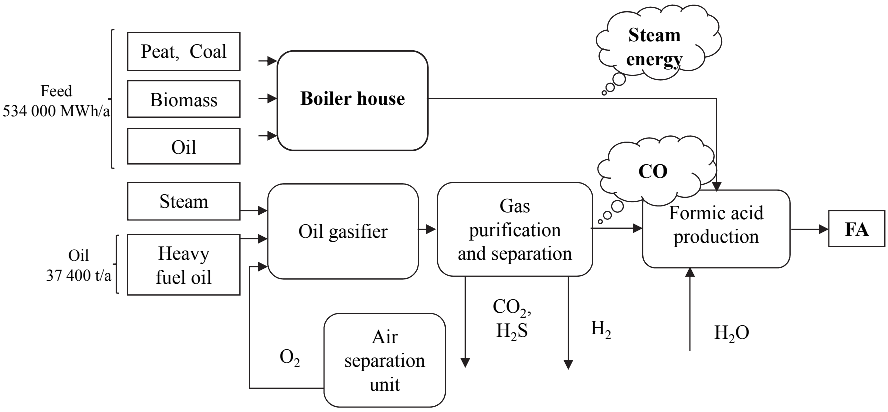

Fig. 5. Formic acid production (re-printed with permission from Inderscience).

According to the environmental permits (Environmental Centre of Northern Ostrobothnia 2007a, 2007b), steam energy for FA production is generated in a boiler house where peat, coal, biomass or oil are used as feedstock. A boiler house consists of several boilers that may utilise all solid fuels. Steam is used as heat energy for distillations in FA production. Synthesis gas (CO + H_2) is generated from heavy fuel by partial oxidation in an oil gasifier. After purification, the CO is fed as raw material to the FA process.

The most important industrial processes for producing synthesis gas and carbon monoxide include gasification of coal, steam reforming / CO_2 reforming (light hydrocarbons up to naphtha), and partial oxidation of hydrocarbons (heavier hydrocarbons) (Bierhals 2001). Kemira applies this partial oxidation process (Uhde Technologies 2010).

2.4.2 Steel production

The steel industry is a significant emissions source. Globally 6–7% of CO_2 is caused by steel manufacturing (Kim & Worrell 2002). The emissions in the steel industry are influenced by used production routes, product mix, production energy efficiency, fuel mix, carbon intensity of the fuel mix, and electricity carbon intensity (Kim & Worrell 2002). The production of steel has increased almost steadily during the last 40 years from 595 Mt/a in 1970 to 1327 Mt/a in 2008 (World steel association 2009). Steel mill emissions are included in the emissions trade scheme (ETS) (The European Parliament 2003). Consequently, it is worthwhile considering new ways to reduce CO_2 emissions.

About 60% of steel is made in blast furnaces (BF) through iron ore reduction (Bernstein *et al.* 2007). Other alternatives, such as scrap steel melting in electronic furnaces and direct reduction of iron are out of the scope of this study as these processes do not produce CO_2 emissions.

A typical BF based steel mill consists of a coking plant, BF, basic oxygen furnace (BOF), power house, hot strip mill and a sinter plant. Process gases are produced in coking plant, in BF and in BOF. Typically, 69% of CO_2 gases originate from BF, 7% from BOF gas and 6% from coke oven. The remaining 18% originate from other fossil fuels imported into a steel mill. Besides considering the origin of CO_2, one should also analyse from which physical locations the CO_2 comes out as emissions. Typically, 39% of CO_2 emissions exit from a power plant, 19% from coke ovens, 14% from a sinter plant, 12% from heating hot stoves in BF, and the rest from other sources (Birat *et al.* 2008).

The literature discusses different ways of reducing CO_2 emissions in the steel industry. As an example, CO_2 capture and storage combined with top gas recycling in blast furnaces, and the use of charcoal instead of coal are considered as possibilities to reduce emissions (eg. Metz *et al.* 2005, Birat & Hanrot 2006, Borlee 2007, Xu & Cang 2010), In addition, Diemer *et al.* (2004) present different ways of reducing CO_2 emissions by seeking for alternative uses of coke oven gases in steel mills.

The new legislation and the emissions trading increase the pressures of finding new environmentally sound solutions. When considering emissions, the entire supply-chain ought to be considered (e.g. Sundarakani *et al.* 2010).

Figure 6 shows a typical production scheme of a steel mill. There are three typical sources where combustible gases can be attained. Coke oven gas contains mainly methane (CH_4) and hydrogen (H_2), while blast furnace and basic oxygen furnace gases contain mainly carbon monoxide (CO). (e.g. De Beer *et al.* 1998, Diemer *et al.* 2004). Energy-rich coke oven gas has uses in normal production processes in steel mills. Blast furnace (BF) and basic oxygen furnace (BOF) gases are often utilised for electricity production (Gielen & Van Dril 1997, Joseck *et al.* 2008). This carbon-based energy produced in a power house, however, produces unwanted CO_2 emissions.

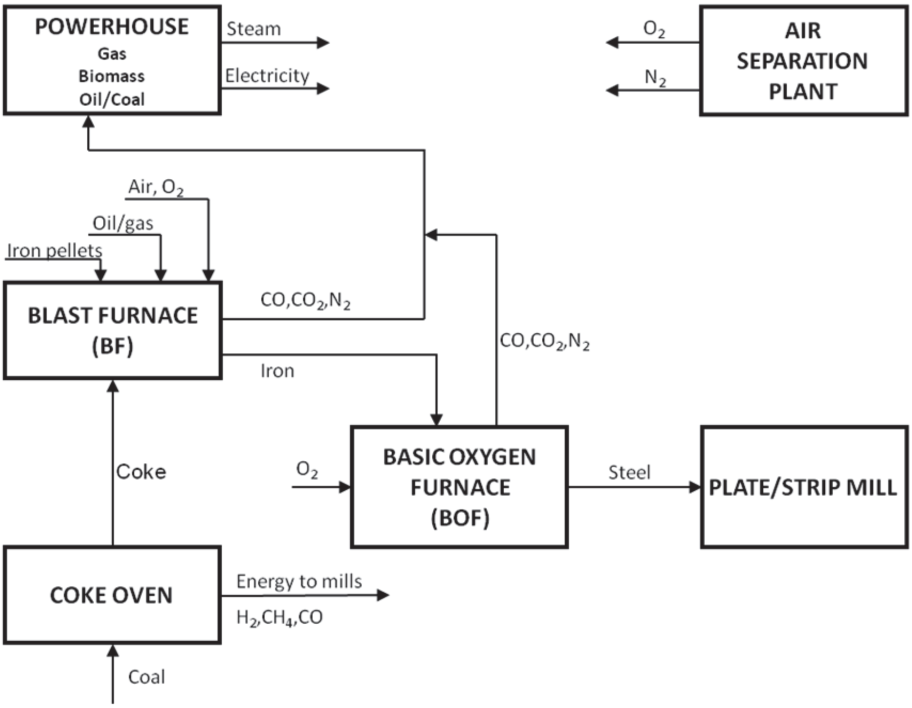

Fig. 6. Typical Steel mill production scheme (re-printed with permission from Scientific Research Publishing.)

2.4.3 Mining industry

The mining and minerals industry faces significant sustainability challenges. The industry must assess its sustainability performance and demonstrate long-term improvements. The mining and minerals sector is currently working towards responding to the sustainability challenges. (Eggert 2002, Azapagic 2004). The mining industry consumes energy for heating and refining processes.

Improving the eco efficiency of the mining industry is currently a topical issue in Finland (Seppälä *et al.* 2002, Salmi 2007, Aro 2009, Ericsson 2010). The Finnish Funding Agency for Technology and Innovation (Tekes) is launching a new technology programme, called Green mining, which goal is to develop Finland to become the global forerunner in eco-efficient minerals production by 2020. In addition, new business opportunities are attempted to be created simultaneously (Tekes 2011).

In 2009, Finland had 8 functional metal ore mines and some were in progress (GTK 2010). In 2010, the total revenues of the Finnish mining industry were some 800 million Euros, out of which metal ores constituted some 550 million. Europe aims to reduce its dependence on imported raw materials. New mines are necessary to meet the increasing demand. The mining industry is considered as one of the growing industries in Finland as the country's soil is geologically rich. The most important mines include, Talvivaara's metal mine, gold mine in Kittilä, chromite mine in Kemi, and metal mine in Pyhäsalmi. The existing metal mines and new potential ones are mainly in Northern and Eastern Finland. (Tuusjärvi *et al.* 2010, Uusisuo 2010).

Talvivaara is one of the most significant mines in Northern Finland. It employs 400 people and is currently producing some 15 000 tonnes of nickel annually. The production is forecasted to increase strongly to 50, 000 tonnes by 2012, which is equivalent to 2% of global nickel production. The open-pit mine is also expected to produce copper, zinc, uranium and cobalt as by-products of the process. Talvivaara is the first mining company that produces nickel bioheapleaching, where bacteria occurring naturally in the area are used to leach metal from the ore. The nickel, copper and zinc recovery units precipitate the metals from their sulphides in the PLS using hydrogen sulphide. (Talvivaara Oyj 2009, Tekes 2010, Mining-technlogy.com 2010).

2.5 CO as a chemical industry raw material

One potential sustainable way to reduce CO_2 emissions is to utilise the CO_2 from industrial processes to produce various chemicals, material and fuels (e.g. Song 2006). CO_2 emissions can also be reduced by removing already formed CO_2 and storing it permanently. Some authors have reported direct conversion of BF gas to dimethyl ether (e.g. Machida *et al.* 1997) and using the gas to produce methanol (Akiyama *et. al*. 1993).

Typical chemical industry processes that can utilise CO directly or after converting to hydrogen with shift reaction are presented in Table 3. Global production volumes are also presented. Methanol, ammonia, and urea have the largest volumes. Acetic acid, formic acid and methyl formate are, however, simpler to produce directly from CO. Methanol and ammonia production require hydrogen with shift reactions and produce CO2, which however, can be utilised for urea production. Nowadays, the above mentioned processes create the CO they require through gasification or steam reforming from coal, oil or natural gas.

Table 3. Typical chemical processes that utilise carbon monoxide.

Product	Net reaction	Global production (Million t/a)	Source
Formic acid	$CO + H_2O \rightarrow HCOOH$	0.5	Yali (2006),
Methyl/Ethyl formate	$CO + CH_3OH/C_2H_5OH \rightarrow CH_3OOCH/C_2H_5OOCH$	n.a.	Reutemann & Kiezcka (2000)
Acetic acid	$CO + CH_3OH \rightarrow CH_3COOH$	8	Cheung *et al.* (2000), China Chemical Reporter (2006)
Methanol	$CO + 2H_2 \rightarrow CH_3OH$	42	Fiedler *et al.* (2000), Floren (2010)
Ammonia	$3H_2 + N_2 \rightarrow 2NH_3$	110	Sukumaran (2006)
Urea	$2NH_3 + CO_2 \rightarrow NH_2CONH_2 + H_2O$	146	Meessen *et al.* (2000), Icis.com (2009)
Hydrogen peroxide	$H_2 + O_2 \rightarrow H_2O_2$	3	Goor *et al.* (2007), Evonik Industries (2010)

The chemical formulas in the above table can also be illustrated as a production process (Figure 7). The figure combines all the discussed chemical products, even though in practice, a single chemical plant produces only one or few of these products. In addition to the presented, there are other potential chemical products that can be produced from CO and synthesis gas based on CO in the future (e.g. Lee *et al.* 1990, Rostrup-Nielsen 2000, Wilhelm *et al.* 2001).

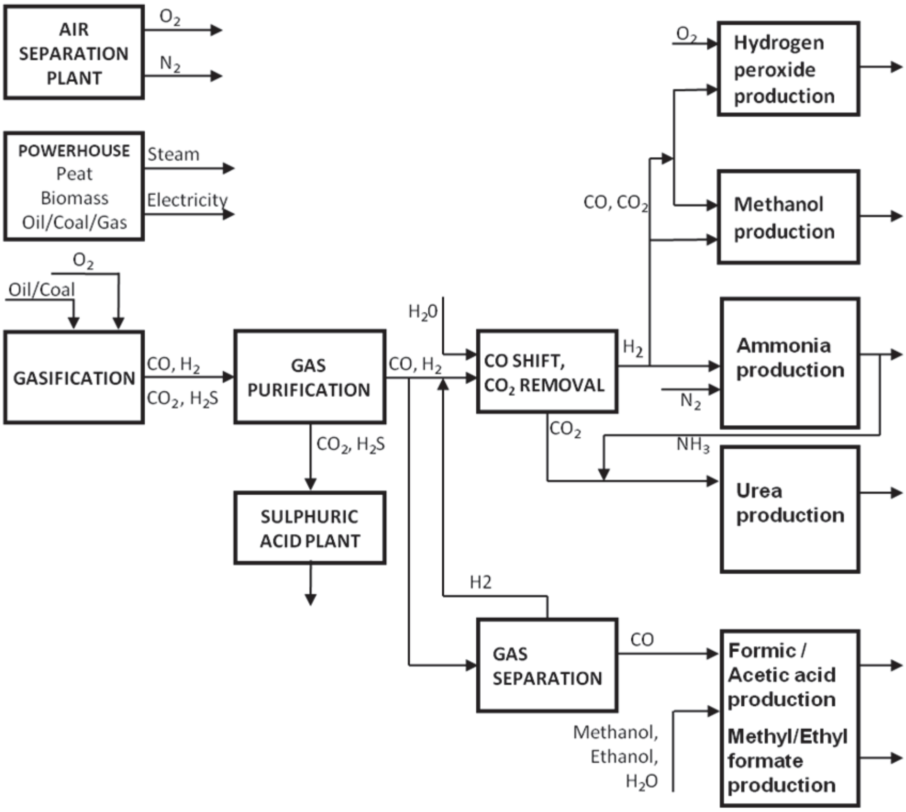

Fig. 7. Production of different chemicals from CO gas (re-printed with a permission).

2.6 Biogas as an industrial raw material

There are many ways to convert biomass into energy, the form of utilisation of which depends on the applications (e.g. McKendry 2002, Demirbas 2005). Biomass containing large quantities of water can be converted to usable energy, biogas, mainly methane (CH_4) and carbon dioxide (CO_2) by using microbes through anaerobic fermentation (Pimentel 2001). Fermentation does not require the raw material to be dry. Anaerobic fermentation can also be seen as a waste management system and an energy recovery process for sewage, industrial sludge and waste water (Green & Byrne 2004). The European energy production from biogas was 8.3 Mtoe in 2009 and the production of electricity was 25.2 TWh. The fast growth of biogas production is based on the European Union policies: and on the renewable energy directive that is aimed at gaining 20% renewable energy share in gross final energy consumption by 2020. It was also based on the directive on landfill of waste, which requires member states to reduce the amount of biodegradable wastes that are disposed of in landfills and to implement laws for waste recycling and recovery. (EurObserv'er 2010). Germany is the leading biogas producer in the world, with enormous development of agricultural biogas plants on farms (Weiland 2010).

Biogas can originate from landfills, from wastewater and industrial effluents or it can be produced in purpose-designed methanation plants. Methanation units are located in farms and in industrial food processing plants. Germany produces over 80% of its biogas 4200 ktoe, using purpose-built methanation plants while Finland has practically no purpose-built production but 30 ktoe landfill and 11 ktoe sewage sludge gas production (EurObserv'er 2010). The legislation in Germany encourages biogas production by providing feed-in tariffs, additional payments for the use of energy crops, and investment supports (Hahn *et al*. 2010). Currently, biogas has not been under focus in Finland as discussion have been concentrated on wood biomass. The national target is to increase the use of purpose-built biogas by 0.7 TWh/a before 2020. Noteworthy is that biogas is not a major energy source for electricity or fuel production in Finland. (Finnish government 2008).

All types of biomass can be used for biogas production as long as they contain carbohydrates, proteins, fats, cellulose, and hemicelluloses as main components. The composition of biogas and methane yield depends on the feedstock type, the digestion system, and the retention time. (Braun 2007).

Various process types are applied for biogas production, which can be classified into two main categories: wet and dry fermentation. All wet processes are operated continuously while dry fermentation can be operated both in batch and continuously. Wet processes dominate in the agricultural sector, where many sources, such as crops, grasses, leaves, manure, fruit, and vegetable wastes or algae can be used both in small and large scales. (Weiland 2003, 2010).

Figure 8. illustrates a biogas production plant in Könnern Germany. This plant utilises corn as raw material and produces electricity by using turbines. The production capacity of the plant is 15 million cubic meter biomethane. Biogas produced in this type of large scale process can be utilised for both energy production and as a raw material for the industry.

Fig. 8. Biogas production plant in Germany (re-printed with permission from Weltech).

2.6.1 Biogas in steam reforming

Steam reforming is a process wherein hydrocarbon from natural gas is heated with steam, usually with a catalyst, to produce a mixture of carbon monoxide and hydrogen used in organic synthesis and as fuel. In steam reforming it is possible to use different hydrocarbon feed stocks in the reactor. Changing from heavier to lighter hydrocarbon, e.g., from propane to methane, does not require significant modifications in the reformer. However, some minor problems may occur, e.g., in the form of coking of the catalyst if process parameters are not tuned to a new feedstock. (Shu-Ren 1998, Turpeinen *et al.* 2008, Holladay *et al.* 2009).

Steam reforming reaction in general uses this formula (Rostrup-Nielsen 2002):

$$C_nH_m + nH2O \rightarrow nCO + (n + 1/2m)H_2. \quad (2)$$

Using biogas-based methane as a raw material in reforming would result in the main reaction being:

$$CH_4 + H_2O \rightarrow CO + 3H_2. \quad (3)$$

Biogas can potentially be produced from grass, silage, willow or reed canary grass (RCG). RCG is considered as one of the most interesting alternatives for a feedstock for bio fuel production in Finland. (Paappanen *et al.* 2008). There are plenty of unused fields in Northern Finland that can potentially be used for producing biogas (Karjalainen 2010).

According to Seppälä *et al.* (2009), one hectare of land can produce about 2500 Nm3 CH4 in Finland but also figures above 3000 Nm^3 CH_4 have been presented (e.g. Lehtomäki 2006, Paavola 2007). However, several studies indicate that heat energy needed in the production, purification and pressurisation of biogas results in the loss of 15–25 per cent out of theoretical maximum (e.g. Persson 2003, Murphy & Power 2009). Using 20% reduction results in net gas production of 2000 Nm^3/ ha.

2.6.2 Biogas in partial oxidation

According to Uhde Technologies (2010) gasification processes are typically non-catalytic processes; combinations of exothermic and endothermic reactions, thermal cracking, steam reforming and so on. The net reaction is exothermic and produces gas that contain mainly CO and H_2:

$$2CH_n + O_2 \rightarrow 2CO + nH_2 \ (1 < n < 4). \tag{4}$$

Hydrocarbon fuels, such as natural gas, refinery gas, bunker C-oil, vacuum residue, vacuum-flashed cracked residue, asphalt and liquid waste can all be used as feedstock for the gasification process (Higman & Van der Burgt 2003).

Typical gas composition of landfill gas is 50% CH_4, 45% CO_2, 5% N_2 and less than 1% hydrogen sulphide (H_2S) (Energy Information Administration 1996). Typically used gasifiers are capable of utilising the landfill gas instead of heavy fuel oil (Turpeinen *et al.* 2008). According to the HSC Chemistry® software programme synthesis gas can be produced when the landfill gas is compressed and fed to the existing idle gasifier. Synthesis gas can be produced without having to purify CO_2 before gasification:

$$CH_4 + \tfrac{1}{2} O_2 + CO_2 \rightarrow 2CO + H_2 + H_2O. \tag{5}$$

CO_2 of the biogas increases the desired CO formation and creates an additional environmental advantage through capturing a part of the CO_2 to the end product instead of releasing it to the atmosphere. In practice, the reaction (5) does not reach equilibrium, but a good ratio of CO – H_2 can be reached according thermodynamic calculations (e.g. Turpeinen *et al.* 2008). More CO is obtained with higher CO_2 concentrations.

Typical concentration of biogas produced through anaerobic fermentation, e.g., from reed canary grass, is similar to landfill gas with slightly bigger CH_4 content and lower CO_2 content (Lehtomäki 2006, Seppälä *et al.* 2009). In principle, partial oxidation is also possible using this gas. If required, CO_2 can be removed from the gas effectively (Rochelle 2009).

2.7 The significance of wood chip moisture in energy production

Moisture is the most important quality factor for using wood biomass as a fuel (Hillebrandt 2009, Sikanen 2009). Moisture has significance on transportation costs due to these costs being directly proportional to weight (Röser *et al.* 2010).

With solid fuels, 10% change in moisture levels has 1–2% impact on boiler efficiency. Power plants are typically optimised for certain moisture levels. Should the moisture be lower than the assumed, the benefit is marginal. However, should the moisture be higher, the penalty has significance (Flyktman & Helynen 2004). Fuel moisture is a limiting factor in biomass combustion due to its effect on heating value. Combustion reaction is exothermic while evaporation of water is strongly endothermic. The self-supporting combustion for most biomass fuels is around 65% moisture content. Above this point, insufficient energy is liberated by combustion to compensate for evaporation and product heating. Practically, most boilers require supplemental fuel when burning biomass in excess of 50 to 55% moisture. Without the additional fuel CO and other products of incomplete combustion may be emitted in greater quantities. (Jenkins *et al.* 1998). *Combustion* processes can be optimised to utilise wood bio-mass with different moisture contents. Fluidised bed boilers can be utilised with moisture content of 30–55%, however the requirements for moisture depend on the individual boiler design. Circulating fluidised bed boilers are the most flexible with regards to moisture content. (Berg 2010). According to Flyktman *et al.* (2011) ordinary moisture for wood biomasses that have not been dried ranges between 45–55%. Moisture content is typically controlled by analysing samples taken from arriving wood chip loads. Moisture analysis takes some twelve hours, making the feedback mechanism slow from the perspective of burning processes. However, instant online measuring methods are currently under development. (Järvinen *et al.* 2006, Fuchs *et al.* 2009, Launonen & Stenlund 2009, Korpilahti & Melkas 2010)

Fuel value for wood can be calculated using the Equation (6) (Alakangas 2000, Kaltschmitt *et al.* 2002):

$$LHV_A = LHV_D \times (1 - M) - \Delta H_{vap} \times M, \qquad (6)$$

where

ΔH_{vap} is the enthalpy of vaporisation
LHV is the lower heating value
LHV_A is the lower heating value on arrival
LHV_D is the lower heating value for dry wood
M is the moisture content on arrival.

Carbon and hydrogen are the components of wood that burn in practise. When hydrogen burns, water is formed, requiring energy for vaporisation resulting in weaker total efficiency in a similar manner as the moisture absorbed in the input wood. According Alakangas (2000), LHV_D = 19.4 MJ/kg is a typical value and variation is 19–20 MJ/kg. Moisture in fuel requires energy for vaporisation, resulting in reduced net energy production. In order to compensate for the energy loss caused by vaporisation, more fuel is required. (Jenkins *et al.* 1998).

Figure 9. summarises the influence of moisture on the real heating value of wood (LHV_D = 19.4 MJ/kg).

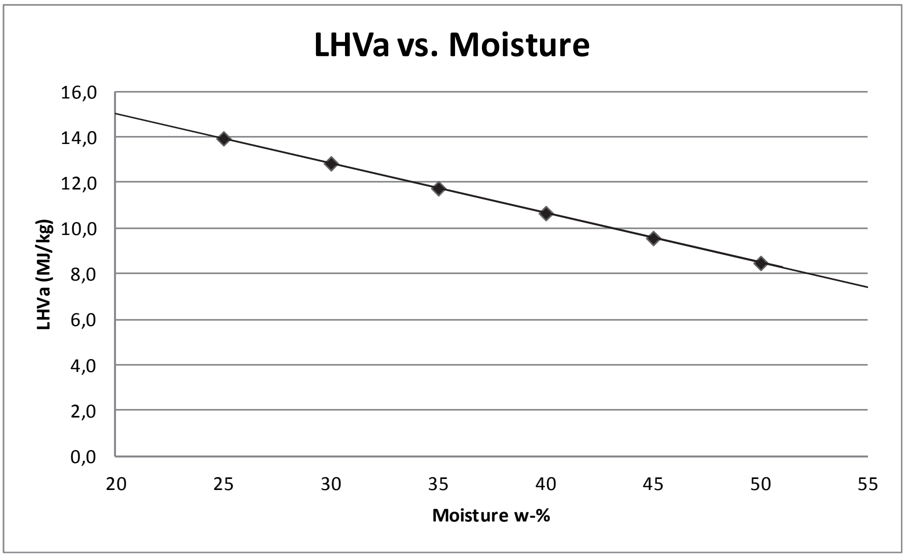

Fig. 9. Influence of moisture on heating value.

Transportation costs depend on the fuel moisture content as in transportation weight is the limiting factor and the prices are determined by weight. Consequently, transportation costs can be reduced significantly if energy wood is allowed to dry. For example, in Britain and in most parts of continental Europe, effective loads are often limited to 20 tonnes because of strict weight limits whereas in Finland loads can be as much as 40 tonnes. It is uneconomical to transport the water contained in wood since part of the available load volume remains unused. In Finland, it is also the volume of the load space becomes a restricting factor for carrying energy wood if the maximum load 40 t is used. (Röser *et al.* 2010). In other words, higher fuel moisture content requires more fuel loads to be transported in order to move the same amount of dry matter. In addition, at power plants, more energy is required to vaporise the water.

2.8 Techno-economic calculations

Techno-economic calculations can be conducted by using different means, and to a varying level of detail depending on the purpose of the calculations. At a rough level, methods such as annuity method, opportunity cost, investment payback period, and scaling investment costs can be used. Annuity method can be used to convert investment costs to annual costs. Purchase costs relevant for the investment are divided along the investment period into equal annuities. Annuities consist of depreciations and interest expenses calculated from imputed rate of interest. Annuity is compared to annual net incomes. Investment is positive if the annual net income at least equals to annuity. (Haverila *et al.* 2005). Annuity can be calculated using Equation 7:

$$AN = \{I \times (1 + I)^n / [(1 + 1)^n - 1]\} \times H, \tag{7}$$

where
AN = annuity
I = interest rate
n = investment period
H = purchase cost.

In order to analyse investment uncertainties, one can prepare investment calculations with different assumptions. For example, investment calculations can be prepared by using three scenarios; optimistic, probable and pessimistic.

Profitability can be analysed by finding out both the optimistic and pessimistic extremes. These two scenarios are, however, unlikely in reality. (Aho 1989)

Opportunity cost is a good way of evaluating alternative production options. Baumol and Blinder (2011) define opportunity cost as follows: *"Opportunity cost of any decision is the value of the next best alternative that the decision forces the decision maker to forgo."*

Investment payback period represents the time that the investment takes to pay its value back, a time that net profits meet the investment costs. Payback time does not provide information on whether the investment is profitable; it only providesits liquidity and financing impacts. The residual value of the investment is not taken into account when calculating the payback time. (Aho 1989, Etelälahti *et al.* 1992). Investment payback time can be calculated using Equation 8:

$$n = H/ S, \tag{8}$$

where
n = payback time in years
H = investment cost
S = investment annual net income.

Industrial investment costs for new investments can roughly be scaled from a known existing case using Equation 9 (Green& Perry 2007):

$$\text{Investment cost} = A \times (B / C) \exp D, \tag{9}$$

where
A = the investment cost for a known case
B = the capacity of the investment to be estimated
C = the capacity of the known investment
D = a case specific exponent.

3 Research contribution

3.1 Formulas and starting values

This doctoral dissertation uses information from the 2010 legislation. Likewise 2010 information is mostly used for raw material price levels, along with partial information from 2009. Statistics are typically updated months, or even half a year after the actual occurrences. The base work of this dissertation and its articles is conducted mostly in 2010.

Table 4 presents the information and prices used in this doctoral dissertation.

Table 4. Relevant information and prices used.

Item	Value
Investment depreciation	15 yrs (Article II), 20 yrs (Article IV)
Interest rate	10%
CO_2 emissions trade cost	10–50 €/t CO_2
Price for CO	50–150 € / 1000 Nm3
Electricity price	40–80 € / MWh
Propane price	600 and 800 €/t
Oil price	250 and 500 €/t
RGC price	6 and 12 €/MWh
Wood chip price	20 €/MWh

This doctoral dissertation utilises the Equations 10–24 presented below. More detailed information on the use of these equations can be found in Articles II–V.

Research question 1 (Article II):

$$\text{Fuel } CO_2 \text{ price} = \text{emission coefficient} \times CO_2 \text{ emission cost} \tag{10}$$

$$\text{Fuel cost} = \text{Fuel consumption} \times \text{Fuel price} \tag{11}$$

$$CO_2 \text{ cost} = \text{Fuel consumption} \times \text{Fuel } CO_2 \text{ price} \tag{12}$$

$$\text{Steam cost} = \text{Fuel cost} + CO_2 \text{ cost} \tag{13}$$

Research question 1.1 (Article V):

$$\text{Additional cost} = \frac{\text{National goal (or required feed)}}{\text{LHVA} \times \text{Additional wood \%} \times \text{Price level}}, \tag{14}$$

where
Additional cost is the additional cost for raw material
National goal = 25 000 GWh
Required feed = 534 000 MWh
LHVA is the lower heating value on arrival (fuel value)
Additional wood % means the additional dry wood required

$$\text{Truck loads} = ((\text{National goal (or required feed)} / \text{LHVA}))/ 35 \text{ tonnes}, \tag{15}$$

where 35 tonnes is an average load.

Research question 2 (Article III):

$$\text{EI} = \text{COvalue} + \text{CO}_2\text{value} - \text{Ecost} \tag{16}$$

where, EI = Economic impact, COvalue = value of CO gas, CO_2value = emissions trading value of CO_2, Ecost = Electricity cost.

Research question 3 (Article IV):

$$\text{Advantage} = \text{cost of propane (or heavy fuel oil)} - \text{cost of biomass} - \text{capital costs} - \text{operational costs} \tag{17}$$

$$\text{Cost of propane (or HFO)} = \text{consumption of propane (or HFO) x price of propane (or HFO)} \tag{18}$$

$$\text{Cost of biomass} = \text{crop yield} / \text{hectare} \times \text{cultivated area} \times \text{price of crop} / \text{MWh} \tag{19}$$

Capital costs are scaled using three true German cases and their investments costs as a starting point (see Equation 20 below) (Green & Perry 2007). Investment costs are converted into annual costs with the annuity method by using 10% rate and 20 years service life.

This study estimates the operational costs of a biogas plant to be 10% of the annual unsupported capital costs following the principles of Smyth *et al.* (2010).

$$\text{Investment cost} = A \times (B / C) \exp D, \tag{20}$$

where A is the investment cost for a known case
C is the capacity of the known investment
B is the capacity of the investment to be estimated
D is a case specific exponent. Values 0.5, 0.75 and 1 have been used.

The economical advantage of utilising landfill gas in the gasifier can roughly be described as:

$$\text{Advantage} = \text{cost of oil} - \text{value of gas} \tag{21}$$

$$\text{cost of oil} = \text{amount of substituted oil} \times \text{price of oil} \tag{22}$$

$$\text{value of gas} = \text{amount of methane} \times \text{price of methane} \tag{23}$$

$$\text{amount of substituted oil} = 3 \times \text{amount of methane} / 2700. \tag{24}$$

3.2 Answering research question 1

Research question 1 is answered by Article II. Article II clarifies whether it is feasible to replace fossil raw materials by wood biomass in the chemical industry's formic acid processes.

In the studied process, Kemira's formic acid production, carbon dioxide is formed in two ways, during *heat energy production* and, at a lesser extent, during the *production of carbon monoxide*. According to the results of this study, fossil raw materials can be replaced with renewable energy, such as wood biomass, in formic acid production systems. Biomass can be used as a fuel in energy production for processes or as raw material in processes. It is possible to utilise renewable energy especially in heat energy production if economically viable.

Heat energy production

Carbon dioxide emissions trading and taxation are among the main factors that can be used by the society to influence fuel selection. Emission trade costs varied from 12–16 €/t CO_2 in 2009 (Nord Pool 2010). These emission trade costs are forecasted to gradually increase to 24 €/t CO_2 by the year 2012 and over 30 €/ t CO_2 by 2020 (Kossoy & Ambrosi 2010, Thomson Reuters 2010). However, possible increase in the price of wood biomass can reduce its competitiveness. This research shows that emissions trade directs the use of heating energy towards the use of renewable energy thus supporting sustainable economy.

Figure 10 illustrates fuel CO_2 prices for different fuels as a function of CO_2 emission cost, covering emission costs between 10 to 50 €/t CO_2. Fuel CO_2 price is the fuel specific emissions cost for CO_2 release. The calculations do not include the new tax imposed on peat, which was introduced in 2011. This tax makes wood biomass more competitive.

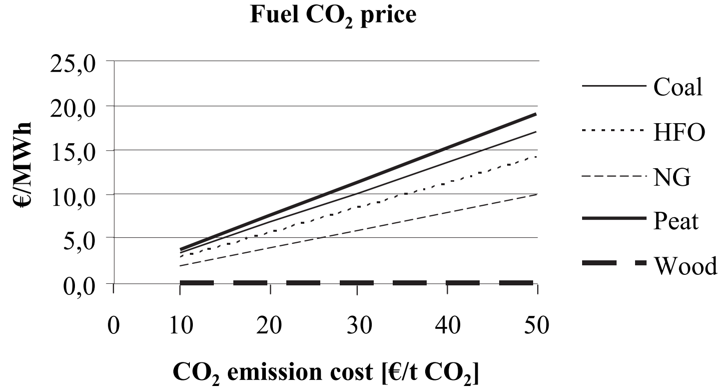

Fig. 10. Fuel CO_2 prices for different fuels as a function of CO_2 emission cost.

Figure 11 presents the annual CO_2 emission costs specific to the case process calculated with real production volumes.

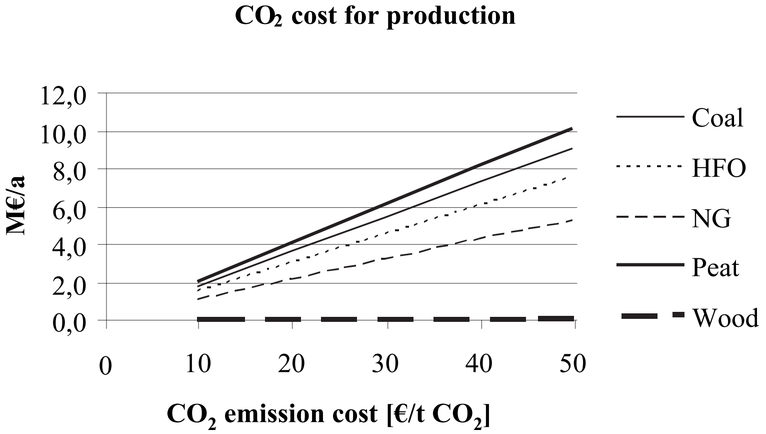

Fig. 11. Annual CO_2 emission costs in the case process.

Figure 12 presents the total annual case specific steam costs for different fuel options as a function of CO_2 emission. As an example on how to read Figure 12, in August 2010 the CO_2 emission cost was 15 €/t CO_2. This equals to 9 million € annual steam costs when using peat, 10 million € for wood, 12 million € for coal, 16 million € for NG and 25 million € for HFO. Should the CO_2 emission cost rise to 30 €/t CO_2, the annual steams costs for the two main alternatives – wood and peat – would be 10 million € and 12 million € respectively. Should the CO_2

emission cost rise even higher, the relative competitiveness of wood would increase even further. Natural gas is not locally available for the case company, but the NG curve is, however, shown for comparison.

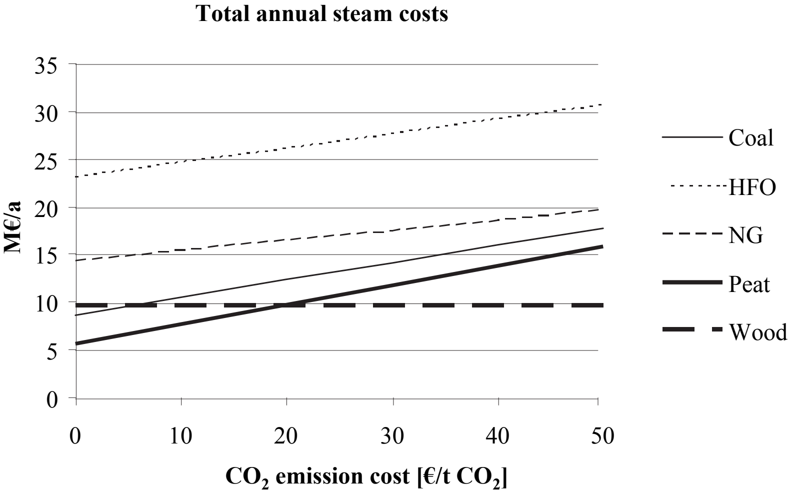

Fig. 12. Annual total case specific heat energy costs.

Figures 10–12 show that peat has the highest CO_2 emission trade costs but lowest total cost when the CO_2 emission trade price is under 20 €/t CO_2. When the CO_2 emission cost is below 5 €/t CO_2, coal becomes the second best alternative after peat. As a rule of thumb, switching from peat to renewable wood biomass becomes worthwhile when the emissions trade costs exceed 20 €/t CO_2. These results are valid with current taxation levels. When the CO_2 emission cost rises above 20 €/t CO_2, biomass/wood becomes the best alternative. If peat was replaced completely by wood chips, the CO_2 emission covered by the emissions trading system would be reduced by 0.381 CO_2t/MWh×534 000 MWh = 203 000 t/a (where 0.381 is the emission coefficient for peat and 534 000 MWh is the required feed energy).

Gas production

In theory, it is possible to utilise wood biomass for carbon monoxide production. However, the technology relating to carbon monoxide production using renewable energy sources is currently under development. The current systems are not directly compatible with this type of solutions.

Synthesis gas production is very capital intensive, and for biomass the investments are even larger, compared to oil (Basye & Swaminathan 1997). Biomass gasification is still under development and it is clear that legislation does not give any significant economic incentive. Therefore, large investments for changing the feed-stocks are not economically viable as they only provide minor improvements in variable costs.

Should all CO_2 emissions be taken into account in the case process, calculations would justify an investment of 17 M€ if the interest rate of 10% and payback period of 15 years would be applied. The price of CO gas can be seen to consist of capital costs and productions costs, with capital costs dominating. This study utilises price information from Blesl and Bruchof (2010) and Basye and Swaminathan (1997) and estimates price as per GJ. The capital cost of coal gasification plants given per GJ of synthesis gas (CO, H_2) output are seen to range from \$13/GJ for bituminous coal to \$17.2/GJ for subbituminous coal. The total syngas production cost decreases with increasing coal quality and ranges from \$15.6/GJ to \$19.3/GJ. When processed to hydrogen the costs are seen as \$11.3/GJ by partial oxidation of fuel oil, \$15.9/GJ by gasification of coal and \$21.7/GJ by gasification of biomass. Based on the above, the CO gas price ranges from 11.3 to 21.7 \$/GJ. By using price \$21.7/GJ investment cost for synthesis gas converted into Euros would be 60 €/MWh. By assuming the efficiency to be fictive 100% and using MWh required in the analysed case, the investment cost of 26 M€ (37 400 t×11.6 MWh/t x 60 €/MWh) can be reached. This investment cost would only cover the share of CO_2, but not any other expenses.

Consequently, the legislation for CO_2 emission trade now and in the near future does not motivate for seeking sustainable options. This is the case even if the CO_2 emissions after gradually being released into the atmosphere while using FA would be included in the legislation.

The coming CO_2 emissions trade will be extended in 2013 to include synthesis gas production (Finnish Government 2011). The extension will not, however, be enough to direct fuel use towards renewable energy. This is due to the liberation of CO_2 in the production of synthesis gas being relatively small while the required investments are enormous. In the studied case, the released quantity is 17 800 t CO_2 during production of 100 000 t FA which has only a value of 0.36 M€ with emission cost of 20 €/t CO_2.

Another viewpoint, which is excluded in the current and coming EU legislation, involves the CO_2 that is brought from fossil fuel to a chemical product, as CO_2 is released to the atmosphere while the product is being used. Case company's annual production of 100 000 t acid results in 94 500 t of released CO_2 which would correspond to 1.89 M€ if CO_2 emission cost of 20 €/t CO_2 were charged. However, the CO_2 that is gradually released to the atmosphere while using carbon dioxide releasing products, is not included in the legislative emission calculations. This is the case even if this factor has a bigger impact on CO_2 emissions. This indicates that the legislation does not cover the entire product life-cycle and that there is a loophole.

3.2.1 Answering research question 1.1

Research question 1.1 is answered in Article V. Article V analyses the economic impact of wood chip moisture to the Finnish economy. Below, the impact of wood chip moisture has been scaled to the Kemira case presented in Article II. The answer to research question 1.1 supports the answer to research question 1.

This study shows that wood chip supply chain typically consists of 1) harvesting, 2) local movement of wood, 3) local storing and drying of wood, 4) chipping, 5) transporting woodchips to the point of use, 6) optional thermal drying, and 7) burning. Significant cost sources include transportation and the burning process.

Typically, wood collected for burning purposes is piled at roadsides and protected from rain water. Industrial drying is only utilised in exceptional cases, when cheap industrial excess heat is available. Wood moisture during storing depends on how well the storage piles have been constructed and how they have been protected. Moisture content also varies during different seasons. Wood provided by different suppliers and locations may have different moisture content. This study aims to assess the economic impact of wood moisture variation.

The calculations assume a truck load to be 35 tonnes in weight. There is also a volume limitation of 140 m^3. However, in the Oulu region the typical average is 35 tonnes. With these assumptions weight is the limiting factor when moisture level ranges between 30–60%. Additional wood percent means the amount of additional dry wood required to compensate for the negative impact of moisture. Additional truck loads is the additional loads required to transport the additional wood. The required number of truck loads is calculated by using Equation (15). Truck loads can be converted into Euros by estimating the average transportation distance and costs per km. This study assumes the average distance of 80 km and transportation cost of 2 €/km, resulting in 2×80×2 = 320 €/load.

Additional raw material is required to compensate for the moisture in order to meet the feed requirements for formic acid production in case Kemira. Table 5 illustrates the additional annual transportation costs and the additional costs for extra raw materials required to compensate for the loss caused by increased moisture content when calculated using formulas 14 and 15. The table describes the significance of these costs for the case Kemira.

Table 5. Additional annual transportation costs and additional cost for raw materials.

Moisture	Additional transportation cost	Additional cost for raw material	Total additional cost
w-%	M€	M€	M€
30	0	0	0
35	0.1	0.2	0.3
40	0.3	0.3	0.6
45	0.5	0.6	1.1
50	0.7	0.9	1.6

Table 5 shows that the total additional costs for moisture content 45 w-% exceed those for 30 w-% by 1.1 M€. This 1.1 M€ is the biggest theoretical impact of moisture in this case. Roughly half of this impact comes from transportation and another half from the weakening burning efficiency.

The market value for the national goal for 25 000 GWh is 500 M€, when using the market price of 20 €/MWh for wood bio-mass. The calculations, thus, show how the significance of moisture for Finland (50 M€) is only 10% of the market value of wood bio-mass.

In addition to the economic calculations conducted above, it is possible to calculate how transport loads, in the case Kemira, increase by some 2300 with a moisture content increase from 30 w-% to 50 w-%. With the above described assumptions, vehicular CO_2 emissions increase by some 360 t/a, when assuming distance as 2x80km, fuel consumption as 30 l/100 km and emission coefficient as 0.283 t CO_2/MWh, respectively Calculated CO_2 emissions increase by some 13 000 t/a when considering the national goal of 25 TWh for the use of wood chip by 2020. However, analysing CO_2 balances is not in the direct focus of this dissertation.

The significance of fuel moisture can potentially be reduced by constructing heat exchangers to collect the energy released from condensing water. There needs to be use for this hype of heat energy for the solution to be viable. Analysing this type of investments is however, out of the scope of this dissertation.

3.3 Answering research question 2

Research question 2 is answered in Article III. Article III studies the possibility of combining steel and chemical productions to reduce CO_2 emissions.

Figure 13 illustrates how steel and chemical productions can be combined regarding gas utilisation. Carbon monoxide from a steel mill can be used for chemical production. This study has utilised Rautaruukki's real production figures as the basis for analyses. The area highlighted in grey illustrates the chemical product lines proposed to be integrated into the proximity of a steel mill. In the constructed model, gases from the *blast furnace* and *basic oxygen furnace* currently taken to a *powerhouse* are now directed to *gas treatment*.

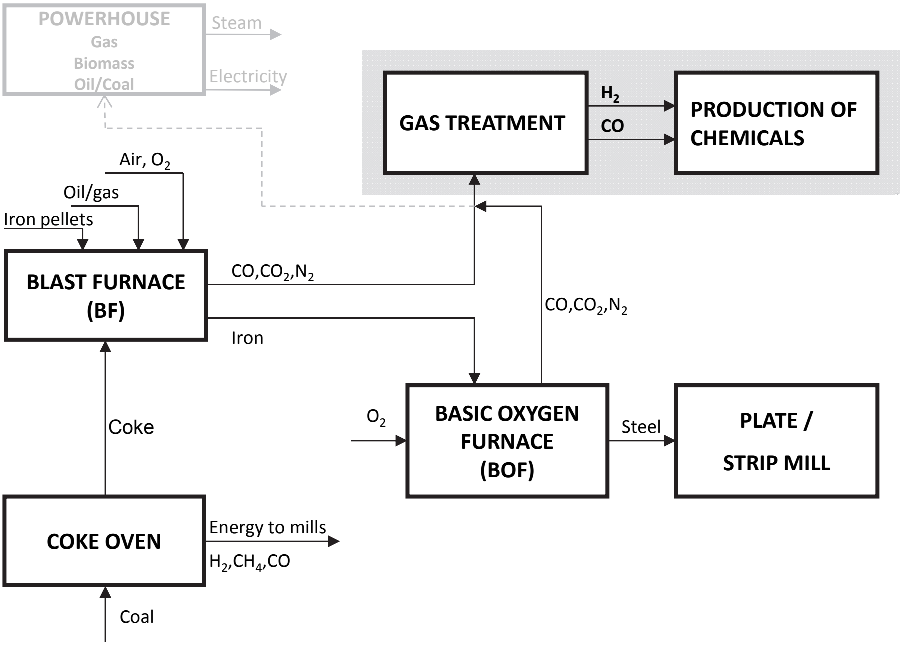

Fig. 13. Constructed process model combining steel and chemical production (reprinted with a permission from Scientific Research Publishing).

Article III combines two different industries by analysing the utilisation of steel industry furnace gases for chemicals production. The reduction of CO gas, a pre-form of CO_2 formed in steel mills, is analysed by considering the utilisation of the CO from furnaces for producing chemical products.

Table 6 introduces the figures used in calculations, including both generic and case specific numbers. Generic figures are obtained from the literature and the case specific ones have been provided by the case steel company. These production figures and gas compositions are typical to steel mills using BF technology.

Table 6. Figures utilised in economic calculations.

Parameter	Value
Yield CO	0.88*
BF gas volume	2 125 million Nm^3/a
BF gas CO concentration	0.24
BOF gas volume	212.5 million Nm^3/a
BOF CO concentration	0.69
Total pure CO volume	578 million Nm^3 / a
Emissions permit of the case steel mill	4.5 Mt CO_2 /a
Density of CO_2	1.98 t/1000 Nm^3
Power plant efficiency	0.3
Heating value of CO gas	3.5 MWh / 1000 Nm^3
Gas price	50–150 € / 1000 Nm^3
Electricity price	40–80 € / MWh
Emissions trade cost	10–40 € / t CO_2

* yield for a VPSA Plant for CO separation from syngas (Xie *et al.* 2006)

Rautaruukki produces a total volume of pure CO of 578 million Nm^3 / a as a furnace side product. This case analyses the possibilities of using this gas for chemicals production and utilises the following prices for calculations: pure CO gas price 50–150 € / 1000 Nm^3, electricity price 40–80 € / MWh. In addition emission trade costs are estimated to be 10–40 € / t CO_2.

Article III indicates that carbon dioxide emissions caused by the steel industry can be reduced by selling CO gas, from furnaces, to the chemical industry. The case also proves the economic profitability of such a transition. Currently, this CO gas is utilised for energy production. Consequently the replacement electricity has to be bought from the markets if CO is used for other purposes. In order for the utilisation of furnace gases for industrial purposes to be viable from an environmental perspective, replacement electricity must originate from renewable sources such as from wood biomass. Tables 7 and 8 show the economic impacts of the proposed arrangement with emissions costs of 20 and 30 € / t CO_2.

Table 7. Economic impact (M€ / a) when emissions cost 20 € / t CO_2.

Emissions cost 20 € / t CO_2			
CO gas price (€ / 1000 Nm^3)	Electricity cost (€ / MWh)		
	40	60	80
50	28	15	3
100	56	44	32
150	85	73	61

Table 8. Economic impact (M€ / a) when emissions cost 30 € / t CO_2.

Emissions cost 30 € / t CO_2			
CO gas price (€ / 1000 Nm^3)	Electricity cost (€ / MWh)		
	40	60	80
50	39	27	15
100	68	56	44
150	97	85	72

The financial benefits of this type of transition can be analysed by acknowledging potential gains and tradeoffs. A steel mill would gain the price obtained for sold CO gas and the impact of emissions trading costs. The tradeoffs would include a steel mill replacing the electricity by energy purchased from the markets. With the current electricity and CO gas price levels, and taking the impact of emissions trading into account, the case steel mill would benefit of some 50 million € annually if all of the CO gas would be sold. Noteworthy is that some half of these benefits come from the CO_2 emissions trading.

From the perspective of the actors in the chemical industry,, the steel industry is an alternative CO gas provider. In a case of a chemical industry operator considering a new investment, they should consider the possibility of locating near a steel industry actor, as less investment is required compared to self-producing the gas on-site from fossil materials. However, in the case of an existing production plant, this type of transition near a steel industry is feasible only if raw material prices increase heavily.

3.4 Answering research question 3

Research question 3 is answered in Article IV. Article IV analyses whether it is feasible for the industry to replace fossil based raw materials with locally produced biogas alternatives. The analysis concentrates on considering the economic impacts of such replacements in real industrial cases.

The analysed cases include one Talvivaara case and two cases for Kemira. The Talvivaara case analyses the possibility of producing the required gas from reed canary grass. The first Kemira case analyses the possibility of producing the required gas from reed canary grass. The second Kemira case analyses the possibility of obtaining the required gas from a local landfill.

The capital costs of a biogas plant have to be taken into account in the calculations. Costs for new investments can roughly be scaled from a known case by using Equation 9.

3.4.1 Case Talvivaara

This case analyses the possibility of replacing propane with biogas in hydrogen production in mining company Talvivaara. In steam reforming it is, in principle, possible to use different hydrocarbon feedstocks in a reactor. Changing from heavier to lighter hydrocarbon, e.g., from propane to methane, does not require significant modifications in the reformer, making this transition possible.

According to the environmental permit, Talvivaara mine produces 4 000 tons of hydrogen annually by using steam reforming process, which requires 15 000 tons of propane as raw material. Currently, Neste oil provides the propane used by Talvivaara (Neste Oil 2010).

Figure 14 illustrates the economic advantage that is obtainable should propane be replaced with biogas. Calculations assume the volumes to be constant equalling Talvivaara's true volumes. Calculations have been made with RCG price of 12 €/MWh and propane prices of 600 and 800 €/t.

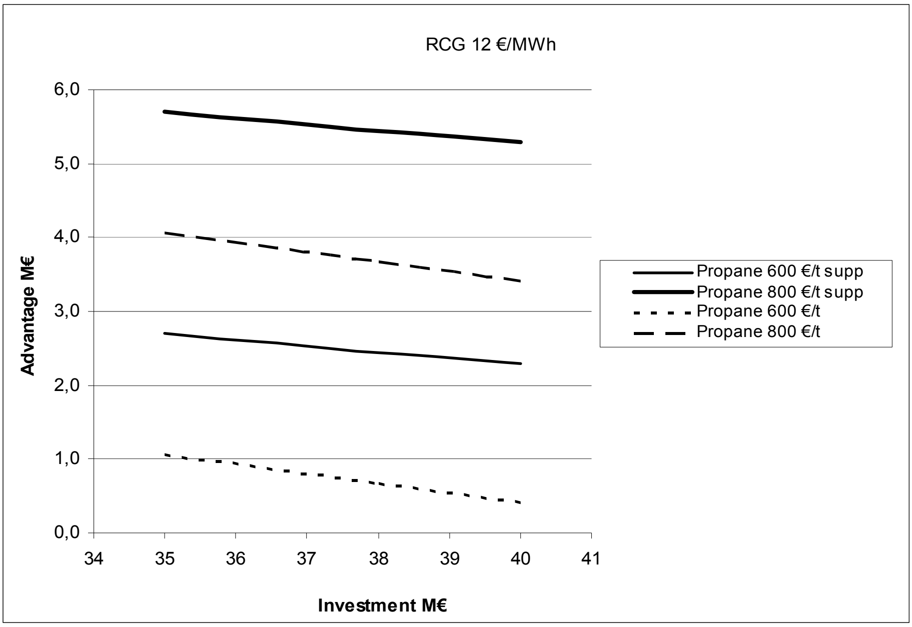

Fig. 14. Annual economic advantage of substituting propane with biogas, RCG price 12€/MWh.

Annual economic advantage of substituting propane with biogas, RCG price 12€/MWh. Currently, there are no significant biogas production sites near the Talvivaara mine. However, there are plenty of farms near the area that could potentially provide the required biogas. There are some 30 000 hectares of unused fields near the Talvivaara site that could potentially be used for producing the required crop. Talvivaara needs 19 million Nm^3 CH_4 annually, which can be served by a cultivation area of 9 500 hectares when RCG is used as the crop.

Calculations in the Talvivaara case included estimating economical benefits of transition from propane to methane produced via anaerobic fermentation by using reed canary grass (RCG) as feedstock. Calculations were made for several different prices of RCG and propane. Investment costs have been calculated by using Equation 20. In addition, the analysis included comparing the situation with and without investment supports for promoting the use of bio-energy. According to the Finnish Government (2001), the maximum investment support for an energy investment is 40% of the total investment. The analysis included acknowledging capital costs, raw materials and operational costs. This study estimates the operational costs for a biogas plant to be 10% of the unsupported investment costs. The waste can be assumed to have a positive market value, as the waste from biogas production can be used as fertiliser. However, this positive impact has not been taken into account.

If the price of RCG is 6 €/MWh, the economic benefit varies between 2–3 M€ when propane price is 600 €/tonne. Should the propane price be 800 €/tonne, the economic benefits increase by 5–6 M€. If the investment supports of 40% is available, the economic benefit is increased by 3 M€/annum. An increase in RCG price from 6 €/MWh to 12 €/MWh decreases the annual benefit by approximately 3 M€.

According to the calculations production costs for methane produced through anaerobic fermentation varies between 25–45 €/MWh, depending on different parameter values. Northern Finland does not have a natural gas pipeline available. However, if natural gas is available, it would be sensible to compare the results to its price. It seems that the price for methane produced from RCG is in line with the price for natural gas, if the investment support is available.

3.4.2 Case Kemira, reed canary grass

Figure 15 illustrates the economic advantage of substituting heavy fuel oil with gas from anaerobic fermentation for Kemira. Calculations have been made for fuel oil prices of 250 and 500 €/t, and for investments ranging between 40–70 M€. Investment costs have been calculated by using Equation 20. Figure 15 presents a case where RCG price is 12 €/MWh.

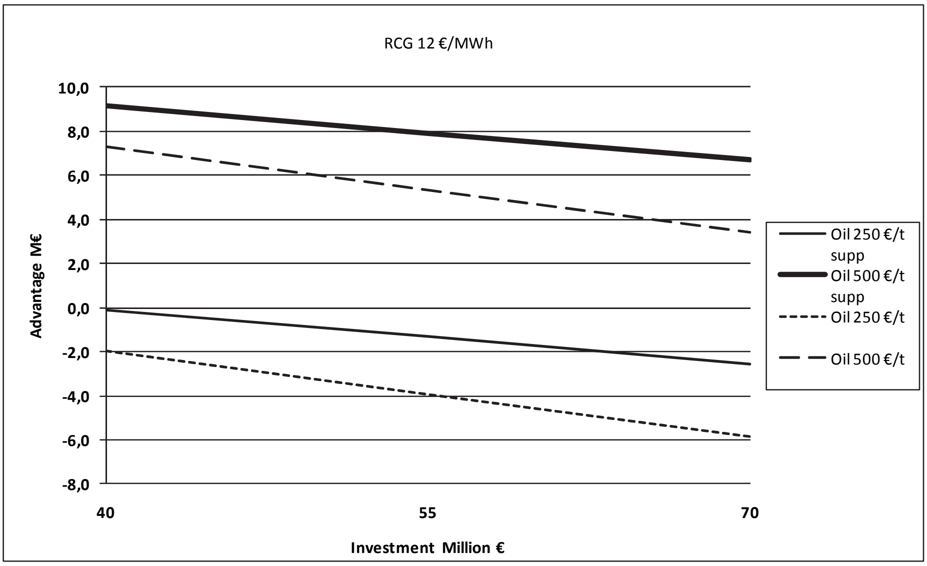

Fig. 15. Economic advantage when substituting oil with gas from anaerobic fermentation, RCG price 12 €/MWh.

If the investment receives a maximum government support of 40%, the net investment cost would be 34 M€ and 42 M€. If reed canary grass price is RCG 6€/MWh, the annual economic benefit for case 2 would be approximately 10 M€ with full investment support. Without government support, the benefit would be near zero. If the price of RCG rises from 6 to 12 €/MWh, the advantage is reduced by 3–4 M€. It is noteworthy that the RCG prices require support equivalent to farming supports typical for food production.

Utilisation of biogas or methane produced through *anaerobic fermentation* from e.g., reed canary grass (RCG), is economically viable and technically possible. This requires industrial investments to produce the gas. Similarly, the farming of RCG and the logistics for transporting RCG to the production site need to be organised.

In order for biogas via anaerobic fermentation to become an economical alternative as raw material, investment subsidies for biogas production and farming are required in the same way as currently for agricultural production. This would mean expanded subsidies, which strongly require new political decisions.

3.4.3 Case Kemira, landfill gas

This case analyses the Kemira company when landfill gas is used as raw material. Around 8 million Nm^3/a biogas is produced in a landfill 3 km from the Kemira production site. Typical gas composition of landfill gas is 50% CH_4, 45% CO_2, 5% N_2 and less than 1% hydrogen sulphide. In this case the methane content is 48% (Kuittinen *et al.* 2010).

Figure 16 illustrates the economic advantage of Kemira if heavy fuel oil is replaced with landfill gas when oil prices are between 250–500 €/t. As the availability of landfill gas is limited in this case, the replacement can only cover 3800 t/a or some 10% of the oil usage. Calculations have been conducted by using the price of wood biomass, a realistic alternative for the area, for landfill gas. It has been assumed that no significant investments are required as the existing equipment is assumed to be compatible. Required investment would include relatively cheap plastic piping between the landfill and the nearby Kemira plant.

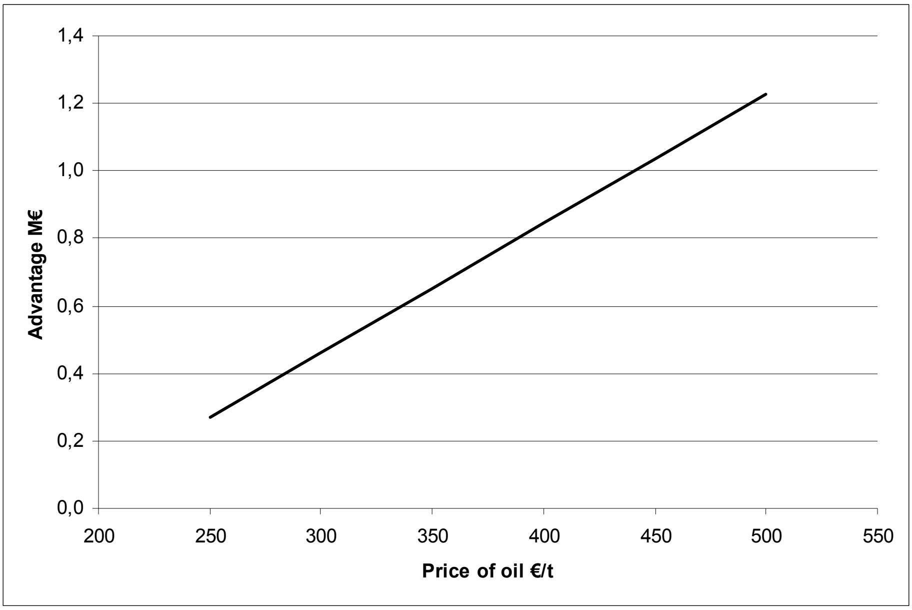

Fig. 16. Annual economic advantage when substituting oil with landfill gas.

The economic advantage of replacing heavy fuel oil with landfill gas varies between 0.4 and 1.2 M€ depending on oil price. The advantage is relatively small as the available volume is limited. In principle, replacing heavy fuel oil with landfill gas can be lucrative, should there be adequate volume of landfill gas available.

The use of *landfill gas* is straightforward and profitable. Nevertheless, the volumes of landfill gas are relatively low, only enabling a partial solution in this case.

3.5 Results summary

This sub-chapter provides brief summaries of answers to each research question.

RQ1 Is it technically and economically feasible to replace fossil raw materials with wood biomass in the chemical industry's formic acid processes?

In the studied process – Kemira's formic acid production – carbon dioxide is formed in two ways: during *heat energy production* and, to less extent while *producing carbon monoxide*. This dissertation indicates that it is feasible to replace fossil raw materials in heat energy production by wood biomass when the emissions trade costs exceed 20 €/t CO_2.

Synthesis gas production is very capital intensive, and for biomass the investments are even larger, compared to oil and biomass gasification is still under development. Therefore, large investments for changing the feed-stocks are not economically viable as they only provide minor improvements in variable costs. Moreover, it is clear that the emissions trade legislation does not provide enough significant economic incentive.

RQ1.1 What is the economic significance of wood chip moisture?

The total additional costs for moisture content in the studied formic acid case for 45 w-% exceed those for 30 w-% by 1.1 M€. This 1.1 M€ is the biggest theoretical impact of moisture in the case of Kemira. Roughly half of this impact comes from transportation and another half from the weakening burning efficiency.

Nationally, the total market value of wood chip bio-mass in Finland is 500 M€, when the national bio-energy goal of 25 TWh is achieved. The results of this dissertation indicate that total costs for moisture content in Finland is annually some 50 M€ higher when using wood bio-mass with 45 w-% instead of 30 w-%.

Roughly half of this increase comes from transportation and another half from the weakening burning efficiency.

> *RQ2 Is it technically and economically feasible to combine steel manufacturing and chemical production when considering one's by-product as other one's raw material?*

The results of this dissertation indicate that utilising steel mills furnace gases for chemical production is economically viable. With the current electricity and CO gas price levels, and taking the impact of emissions trading into account, the case steel mill, Rautaruukki, would benefit of some 50 million € annually, if all of the CO gas would be sold for chemical production. Noteworthy is that some half of these benefits come from the CO_2 emissions trading.

> *RQ3Is biogas a technically and economically feasible alternative as raw material for industrial synthesis gas users?*
> *Biogas can be produced from biomass via anaerobic fermentation or obtained directly from a landfill.*

This study analyses anaerobic fermentation using reed canary grass-based biomass. RCG can be produced by local farmers in currently unused fields. The results show that using biogas is economically feasible. However, this type of arrangement may require government farming subsidies in a similar manner as currently for food production. In addition, investment supports may be required to ensure profitability.

Using landfill gas is well feasible; however, gas volumes available are too low for industrial scale use in the studied case.

4 Discussion

4.1 Theoretical implications

This doctoral dissertation identifies five industrial processes that have the potential for large scale solutions that could be considered green through analysing 262 environmental permits. This dissertation creates new case-specific knowledge on how to replace fossil raw materials in the industry with renewable solutions.

Previous literature concerning formic acid production has not widely discussed carbon dioxide perspective (e.g. Leonard 1979, Hydocarbon processing 1983, Marsella 1994, Reutemann & Kieczka 2000), There are current discussions on developing environmentally cleaner formic acid processes (Hayes *et al.* 2006, Chang *et al.* 2007, Aresta and Dibebetto 2007). Traditionally, the steam required in FA production (methyl formate processes) is produced by using fossil fuels. This study provides new knowledge by showing calculations for developing traditional methyl formate processes towards increased environmental friendliness. Instead of completely re-inventing these processes, this study proposes the improvement of existing ones to fulfil green requirements.

This dissertation confirms the findings of Ranta *et al.* (2007) on emission trading costs of 20 €/tonne CO_2 being the critical threshold for wood becoming a viable alternative for fossil fuels in energy production. This research complements previous research (Koljonen & Savolainen 2005, Kirkinen 2010) by providing more tangible economic calculations for several raw material alternatives obtainable in Northern Finland.

Besides analysing the energy production, this research also analyses the potential of using wood biomass as a raw material for synthesis gas production. Wood biomass is currently studied for the purpose of synthesis gas production (Huber *et al.* 2006, Van der Drift & Boerrigter 2006, Kurkela 2009, UPM 2007, Stora Enso 2009).This dissertation provides new information for the existing literature by indicating that the required investment costs are too vast for the green transition to be currently viable in the studied scale.

The literature includes a vast number of publications that discuss emissions trading (e.g. Frondel *et al.* 2008, Sijm *et al.* 2008, Kossoy & Ambrosi 2010). Emission trading acknowledges the CO_2 created immediately while producing products and consuming fuel (Sundarakani *et al.* 2010), however, it does not cover CO_2 emissions over the product life cycle by ignoring the CO_2 formed while using products. This dissertation provides new information for the existing literature by pointing out this gap in the existing emission trading legislation.

The existing literature covers possibilities for emissions trading mainly concentrating on single industrial sectors (Hidalgo *et al.* 2005, Neuhoff *et al.* 2006). This doctoral dissertation creates new information on the possibilities of emission trading by proposing combining different industrial sectors and seeking for new alternatives in a more radical manner. This research proposes that the side products of the steel industry, particularly carbon monoxide, can be used as a raw material for chemical production.

This dissertation also provides new insights for biogas literature by pointing out how farms can be utilised for bioenergy production in a different manner than typically discussed in the literature (Lehtomäki 2006, Murphy & Power 2009, Smyth *et al.* 2010). Literature, particularly in Finland, typically assumes that both bioenergy production and use are dispersed (Paavola 2007). In Germany there are examples of large scale production sites where produced electricity is fed into the national grid (Weiland 2010, Weltec Biopower 2010). This study presents calculations for centralised bio utilisation in large industrial sites.

Contrary to biomass fermentation, wood moisture has significance in burning processes (Demirbas 2004, 2005). Likewise, contrary to general understanding, this study proves how the moisture does not have as great economic significance. However, the existing literature seems to correctly understand the significance of moisture (Alakangas 2000, Kaltschmitt 2002); thus, this dissertation is in line with the existing literature. Modern combustion plants have been designed in a manner that they allow the use of moist biomass (Khan *et al.* 2009).

The calculations presented in this dissertation can be used as an aid for evaluating the impact of the Finnish national goal to increase the use of wood chips for energy production on the transport sector. Ranta & Rinne (2006) have studied the transport of wood chips and loose residues, analysing technical matters rather than covering the economic impacts. Hence, this dissertation provides new information for the transport sector.

As a whole, this research provides new information through calculating the economic impact of moving towards new solutions in the industry of Northern Finland. Consequently, this research complements the existing literature on sustainability (e.g. Saikku *et al.* 2008), regional development (e.g. Alanne and Saari 2006) and employment (e.g. Järvelä *et al.* 2009). This doctoral dissertation complements the existing literature on emissions trading by providing tangible calculations for converting existing industrial processes towards sustainability. The results can be used to argue for or against renewable energy use.

4.2 Practical implications

Regions considering their development strategies ought to consider whether or not they can benefit from the trend of using renewable energy. This doctoral dissertation presents calculations that enable the assessment of the economic impact of moving towards solutions that are considered greener by presenting tangible calculation for multiple cases. Incentives provided by the European Union and national governments, open up possibilities for the regions to create jobs and find alternatives for current farming.

Employment opportunities can be created in multiple ways. Existing businesses can improve their competitiveness by utilising the provided opportunities. New investments may boost local economies and the transport sector may find new business with bio-fuels. Furthermore, new activities may be required in harvesting and farming.

The implications of this dissertation include pointing out how *regional areas* can promote sustainability by analysing current use of fossil raw materials in their local industry. Replacing fossil raw materials with green alternatives can be assessed once understanding the current situation. Also, innovative solution for combining existing industries is worthy of deeper scrutiny as one sector can potentially provide raw materials for another so that the whole scenario created is better than the current solution. By acknowledging the new ‘greener’ legislation and the potential impact of government subsidies, the change may be profitable for the industrial actors.

Finland’s share of global CO_2 emissions is around 70 million tonnes annually, including natural release from the nature. The CO_2 emissions notified totals some 40 million tonnes in Finland. The share of Northern Finland is some 6 million tonnes. Rautaruukki’s share is some 4 million tonnes and Kemira Oulu plant’s 0.2 tonnes. Talvivaara’s share of CO_2 emissions is currently marginal. (Bionova Engineering 2009, Monni 2010, Statistics Finland 2011) According to this dissertations, combining the steel and chemical industries would reduce CO_2 emissions by 1.1 million tonnes, while replacing the use of peat by wood at Kemira would result in CO_2 emission reduction of 0.2 million tonnes.

Regional decision makers may utilise the calculations presented in this doctoral dissertation. *Biogas* utilisation is often assessed as decentralised options by considering biogas production in farm sites. This study indicates, however, that a centralised option at industrial sites may be an attractive alternative. The crop used for biogas production should obviously be arranged at farms. In addition, constructing biogas producing units at industrial sites potentially enables the development of other biogas applications. Similarly, building pipelines to other biogas users or vehicle uses are potential options. The use of biogas can be promoted by identifying existing industrial sites currently using fossil based gas as raw material and by analysing whether they can utilise biogas. Case specific calculations can be made by using the examples presented in this study.

One potential option for Northern Finland to use bio-energy is to encourage current farms to produce *reed canary grass* (RCG). It is possible to calculate production costs for biogas-based methane produced from RCG by acknowledging capital costs, raw materials and operational costs. This doctoral dissertation includes analysing a theoretical transition in Talvivaara's mine for replacing fossil based propane with a bio-alternative methane. The results show that with an RCG price of 12 €/MWh and with government supported investment costs of 40–70 M€, the production costs for methane required by Talvivaara mine would be 28– 35 €/MWh. Without government support the production costs for methane would 34–45 €/MWh. Fossil raw material prices are rising; consequently anaerobic fermentation may become a more competitive option for reducing the need for subsidies.

In reality, a farmer's earnings consist of farming subsidies and earnings from the actual farming. For example, total farming subsidies for a 100ha farm would be 600€/ha*100ha = 60 000€ (where, 600€/ha is an average subsidy paid in Finland (Paappanen *et al.* 2008), and 100ha is assumed subsidised farming area). If the farmer would gain 12€/MWh when farming reed canary grass, the total gain for the farmer would be 12€/MWh*25MWh*100ha = 30 000 € annually (where, 12 €/MWh is the assumed price, 25MWh yield/ha annually (Lehtomäki 2006, Paavola 2007), 100ha is the assumed farming area). As a consequence, farming subsidies are double compared to farming gains and only 1/3 comes from farming gains and 2/3 from subsidies.

Landfill gas is another possibility for obtaining bio raw materials. The implications of this study include that municipalities with large landfill sites could potentially utilise the principle presented for Kemira case 1 by identifying industrial sites that use oil-based synthesis gas. This dissertation shows how landfill gas only becomes a realistic option once the landfill gas input is large enough to meet the industrial needs. Noteworthy is that this research does not compare the long term ecologic impacts current and new use of landfill gas proposed in this study. This study merely conducts techno-economic calculations on the potential new industrial use.

Managers of companies with high energy consumption and/or high usage of fossil raw materials in their products can utilise the results of this dissertation the most. The managers should conduct similar calculations, as was done in this study, by using figures that are relevant to their processes and raw materials.

Traditionally industries are assumed to take care of their challenges independently and internally. In contrast to this conventional thinking, this doctoral dissertation raises a possibility of finding solutions towards sustainability by *combining two different industrial sectors*. In this research, an example is given on how to combine steel and chemical production, including utilisation of incentives given by the emissions trading and the governmental support given for ‘green’ investments. This type of reasoning resembles ecological industrial park initiatives.

This study provides a potential model for managers in the steel industry for calculating alternative models for operations by using their own exact case-specific figures. This study supports the idea of combining economic facts with the strive towards sustainability. This study gives a tangible example on calculating CO_2 emissions trading in economic terms. The managers in the chemicals industry, especially those considering new investments, may find the proposed transition as a new opportunity to obtain raw materials without extensive investments to production capacity for CO gas.

When combining a steel mill and chemical production, the trade-off of utilising CO for other purposes other than traditional electricity production in a boiler house, is that electricity must be bought from the market. Moreover, other alternatives such as combined heat and power (CHP), is not a problem-free solution as steel mill has extensive heat available and consequently, new heat is not required. Neither is a condensing steam turbine a solution as the electricity produced in this way is not competitive compared to market prices.

Moisture is the most important quality factor for using wood biomass as a fuel. Moisture has a significance on transportation costs because these costs are directly proportional to weight. This doctoral dissertation provides calculations on the impact of fuel moisture for the formic acid production case using wood chips. Moisture content in wood bio-mass typically ranges between 30–45 w-% when delivered to a power plant. The results of this dissertation indicate that total costs for moisture content in the case is annually some 1.1 M€ higher when using wood bio-mass with 45 w-% instead of 30 w-%. Roughly half of this increase comes from transportation and another half comes from the weakening burning efficiency. If the national scale is considered and the national bio-energy goal of 25 TWh is achieved, the total market value of wood bio-mass would be 500 M€. The calculations thus show how the national significance of moisture is only 10% of the market value of wood bio-mass.

Actors in the bio-energy field should understand that wood moisture has true significance only for small power plants that are not capable of utilising moist raw material. Larger power plants are typically capable of utilising air-dried wood bio-mass with moisture levels between 30–50 w-%. However, it is desired that the moisture content remains roughly at a constant level. Continuous moisture content measurement would ease the optimisation of combustion process. Properly organised air-drying is the simplest and cheapest measure to decrease transportation costs and improve combustion.

Legislators developing regulations for emissions trading may find the results of this dissertation to be beneficial. This study highlights how the current legislation is not covering enough and does not include all the aspects influencing CO_2 emissions. Legislators ought to acknowledge the CO_2, originating from fossil fuels, released to the atmosphere while a product is used. The new legislation, which will be effective in 2013, guides the production processes, but not the CO_2 release when a product is being used.

This doctoral dissertation identified the following significant alternatives for producing synthesis gas: *biomass gasification*, *landfill biogas*, biogas via *anaerobic fermentation*, and using *steel mill gas* which is an industrial by-product.

Table 9 initially summarises the pros and cons of these four possible ways of producing synthesis gas for the analysed industrial cases. *Technology maturity* clarifies whether existing technologies can be utilised. *Investment costs* clarify the magnitude of new investments required. *Operational costs* refer to cost of production. *Operational feasibility* refers to the ease of use and reliability of operations. *Raw material availability* clarifies whether the raw material is already available. *Tax payer view* refers to the need of subsidies. The researcher utilised the following markings while initially estimating the feasibility of different alternatives: (+) good, (++) excellent, (–) poor, (—) very poor.

Table 9. Comparison of four possible ways of producing synthesis gas.

	Biomass gasification	Landfill biogas	Anaerobic fermentation biogas	Furnace gas from steel mill
Technology maturity	–	++	+	+
Investment costs	—	++	–	+
Operational costs	–	+	+	–
Operational feasibility	–	++	+	+
Raw material availability	+	—	–	+
Tax payer view	+	++	—	+

Landfill gas seems technically and economically a solid option. However, in the studied region, the volumes available are too low for industrial application as the only gas source. Biogas produced via anaerobic fermentation seems viable both technically and economically, but requires significant government support for both investments and farming. Using industrial by-products as raw material for chemicals production seems feasible technically and economically when considering new industrial investments. Steel mill gas is a potential option as a source for synthesis gas, but is not a widely considered alternative in the chemical industry. Regardless of biomass gasification being a discussed topic in Finland, there are many aspects requiring further development before being considered as a feasible option for synthesis gas production.

4.3 Reliability and validity

According to Bryman and Bell (2007), reliability and validity of qualitative research can be assessed by answering the following four questions:

1. How trustworthy are the results?
2. Are the results valid in another environment?
3. Are the findings likely to occur at other times (repeatability)?
4. To what extent have the researcher’s own values influenced the results?

How trustworthy are the results?

The information on the studied industrial cases – their production volumes, material and energy consumption – are obtained from environmental permits and other publicly available documents. Therefore, this information can be considered as trustworthy. The only weakness lying in the fact that the information may already be a few years old. On the other hand, due to the nature of the sector, any changes may occur relatively slowly.

The technical analysis conducted in this research include utilising literature-based information on unit processes, such as steam reforming, gasification, making biogas and so on. The solutions presented in this dissertation are based on understanding the analysed unit processes. New potential solutions are assessed by combining new elements into the existing unit processes. These type of considerations are engineering-based and can potentially contain some minor mistakes. However, the main logic can be considered as sound and trustworthy.

The results of this dissertation are based on techno-economic calculations and publicly known price information as well as scientific literature. The results are trustworthy in the case if the calculations are correct. Should there be changes in the input figures, such as market price fluctuations, the results would change accordingly.

Utilising the results of this dissertation at industrial plants would require large investments. Detailed case-specific calculations and risk assessments are required for making such investment decisions. The results of this dissertation can be considered as directional and case-specific figures are required.

With regards to producing biogas from reed canary grass via fermentation, one must understand that this is a new issue in Finland and there are no large-scale existing supply chains for this matter. Therefore, the calculations are only directional. In order to make exact calculations, one must wait for the sector to develop further.

With regards to wood moisture, this dissertation makes an assumption that the moisture level remains constant; however, wood moisture varies throughout the year. Nevertheless, the purpose has been to provide a level of magnitude, a purpose this research serves well. Exact case specific calculations, including moisture variations, must be conducted when considering true applications.

Are the results valid in another environment?

The results are technically applicable in another environment. However, economic profitability must be assessed case specifically. The calculations can be trusted and the results are valid provided that the input values are similar in other cases. If the raw material prices are different in other environments, or if the volumes are different, the calculations might provide somewhat different results. For example, the way raw materials are taxed may influence the competitive position between peat and wood.

The question whether results are valid in another environment strongly depends on the raw material and energy prices. For example, should an area consider constructing a chemical plant, case specific calculations must be conducted. Companies have a tendency to seek for locations that are close enough to markets and where the raw material prices are favourable.

Are the findings likely to occur at other times (repeatability)?

Another researcher would receive the same results at other times should there be no changes in the input information. However, if there are changes in the input information, the results will change accordingly. For example, if the taxation on peat will increase in the future, wood would become more competitive. Similarly, if the availability of wood becomes an issue due to wood being strongly desired by competing uses, the price of wood would increase and the results of the calculations would change. This dissertation does not take a position on the availability of wood and consequent price implications of the competitive use of wood for energy production as well as making pulp are excluded in the calculations.

The price relations of raw materials and energy change as a function of time, depending on factors such as legislation. Therefore, the calculations are not valid in a long term. The results are also influenced by changes in farming policies and investment subsidies. These aspects may change as a function of time, thereby altering the original setting.

To what extent have the researcher's own values influenced the results?

In general scientific research is challenging to be conducted with full objectivity. However, the more exact the research is in nature, the closer to objectivity one can claim to be. This research emphasises techno-economic calculations that can be considered as neutral. However, to an extent the pre-setting may have been influenced by the researcher's own values and the professional engineering background of the researcher.

When discussing green matters, this dissertation analyses the impact of legislation, which can be considered as a fact. This dissertation does not attempt to take a position on the rightfulness of the legislator's decisions. Therefore, the researcher's own conceptions over environmental aspects have been possible to leave to the background and the pre-setting has been as neutral as possible.

4.4 Recommendations for further research

Reduction of industrial CO_2 emissions can be considered to contain numerous issues and aspects. For practical reasons some relevant issues have been left outside the scope of this dissertation, leaving room for future studies.

Potential future research could include analysing country specific emission trends, whether their emissions in reality are increasing or decreasing, regardless of global aims to reduce emissions. In particular, there is room for studies analysing which reduction methods are effective and which are not.

The current discussion acknowledges environmental impacts caused by the manufacturing of products, but leaves the product life-cycle assessments outside their analysis. However, for example, urea releases some 100 million tonnes of CO_2 to the atmosphere while being used. Analysing the significance of this type of emissions during product use would be another topic for future research.

Man-made photosynthesis and analysing the potential of binding CO_2 artificially from the atmosphere by using chemicals are among interesting future research topics. Nonetheless, these types of topics are currently close to fiction, yet conducting techno-economic calculations would provide more tangibility to the discussions.

The impacts of European efforts to mitigate global climate change are limited unless countries such as China, India, Russia, or the USA also make significant efforts. It would be interesting to see calculations on the global significance of each European effort to the date. It must be noted that the global emissions currently are 31 giga tonnes of CO_2 eq and aims to reach 5 GT are simply unrealistic without heavy reduction of the human population. Furthermore, it would be interesting to study the true climate impact of decisions such as the recent decisions made by Germany to close its nuclear power plants. This may, in practice, increase the use of coal.

This dissertation considered the reduction of emissions of large industrial actors. However, the manufacturing industry only covers a fifth of global emissions. Consequently, it would be interesting to see similar calculations from other areas outside the manufacturing industry.

Global industrial sector organisations consider means for reducing emissions. It would be interesting if the research would compare the results of different efforts and make conclusions on what is effective and what is not.

This doctoral dissertation is tangible techno-economic in nature. The same issues would be interesting to study also from the perspective of social science, war logic, game theory, beneficiaries, sufferers, and so on.

References

Aall C & Norland IT (2005) The use of the ecological footprint in local politics and administration: results and implications from Norway. Local Environment 10(2): 159–172.

Aho T. (1989) Investointilaskentamenetelmät. 2nd ed. Vaasa, Weilin&Göös.

Akiya N & Savage PE (1998) Role of water in formic acid decomposition. AICHE Journal 44(2): 405–415.

Akiyama T, Sato H, Muramatsu A & Yagi J (1993) Feasibility study on blast furnace ironmaking system integrated with methanol synthesis for reduction of carbon dioxide emission and effective use of exergy. ISIJ International 33(11): 1136–1143.

Alakangas E (2000) Properties of the fuels used in Finland (Finnish). Espoo, VTT. Research Notes: 2045.

Alanne K & Saari A (2006) Distributed energy generation and sustainable development, Renewable and Sustainable Energy Reviews 10(6): 539–558.

Aldy JE, Barrett S & Stavins RN (2003) Thirteen plus one: a comparison of global climate policy architectures. Climate Policy 3(4): 373–397.

Anttila P (2005) Ilmaisu, teos, tekeminen ja tutkiva toiminta. Hamina, Akatiimi.

Aresta M & Dibenedetto A (2007) Utilisation of CO2 as a chemical feedstock: opportunities and challenges. Dalton Transactions (28): 2975–2992.

Arvola J Muhos M, Belt, P & Kess P (2011) Renewable energy in chemical industry – The case of formic acid production. International Journal of Sustainable Economy 3(4): 381–394.

Arvola J, Belt P, Harkonen, J & Mottonen M. (2011) Replacing fossil raw materials by using renewable sources in Northern Finland. 2nd International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS2), 19–21 June, 2011, Nisyros – Greece, proceedings.

Arvola J, Harkonen J, Mottonen M, Tervonen P & Haapasalo H. (2011) Combining steel and chemical production to reduce CO_2 emissions. Low Carbon Economy 2(3): 115–122.

Arvola J, Belt P, Harkonen J, Kess P & Imppola R (2012) Biogas as an option for industrial applications. International Journal of Sustainable Economy 4(1).

Arvola J, Belt P, Härkönen J, Möttönen M & Kess P (2011) Economic impact of moisture in wood-based bio-fuels, TIIM 2011 Conference, June 28-30, Oulu, Finland.

Aro T (2009) Preconditions and tools for cross-sectoral regional industrial GHG and energy efficiency policy—A Finnish standpoint. Energy Policy 37(7): 2722–2733.

Azapagic A (2004) Developing a framework for sustainable development indicators for the mining and minerals industry. Journal of Cleaner Production 12(6): 639–662.

Barham HN & Clark LW (1951) The Decomposition of Formic Acid at Low Temperatures, Journal of the American Chemical Society 73(10): 4638–4640.

Basye L & Swaminathan S (1997) Hydrogen production costs—a survey. USDOE Assistant Secretary for Energy Efficiency and Renewable Energy. Doi: 10.2172/67(4693)DOE/GO/10170-T18.

Baumol WJ & Blinder AS (2011) Economics: Principles and Policy. 12th ed. Mason Ohio USA, Cengage Learning.

Berg E (2010) Foster Wheeler Boilers. Interview and letter.

Berndes G, Hoogwijk M & van den Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy 25(1): 1–28.

Bernstein L, Roy J, Delhotal K, Harnisch J, Matsuhashi R, Price L, Tanaka K, Worrell E, Yamba F & Fengqi Z (2007) In Metz B, Davidson O, Bosch P, Dave R & Meyer L (eds) Industry in Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press: 447–496.

Bierhals J (2001) Carbon monoxide: Ullmann's Encyclopedia of Industrial Chemistry [Homepage of John Wiley & Sons]. URI: http://mrw.interscience.wiley.com/emrw/9783527306732/ueic/article/a05_203/current/html?hd=All,Gasification#a05_203-sec1-0004. Cited 2010/04/01.

Bionova Engineering (2009) Greenhouse gas balance in Northern Ostrobothnia (in Finnish). Ylivieska, Union of Northern Ostrobothnia.

Birat J & Hanrot F (2006) Ulcos: The European Steel Industry's effort to find breakthrough technologies to cut its CO2 emissions significantly [Homepage of European DG Commission Research]. URI: http://www.ulcos.org/en/docs/Ref17%20-%20ULCOS_%20Korea.pdf. Cited 2010/07/07.

Birat J, Lorrain J & Lassat Y (2008) The CO2-Tool: CO2 Emissions & Energy Consumption of Existing & Breakthrough Steelmaking Routes. Proceedings of the 4th Ulcos seminar, 1–2 October 2008, ArcelorMittal, Maizieres-les-Metz: 1.

Blesl M & Bruchof D (2010,) Syngas Production from Coal. Stuttgart, IEA ETSAP.

Borlee J (2007) Low CO2 Steels-ULCOS project [Homepage of IEA Deployment workshop]. URI: http://www.iea.org/work/2007/demand_side/borlee.pdf. Cited 2010/07/07.

Braun R (2007) Anaerobic digestion: a multi-faceted process for energy, environmental management and rural development. In Ranalli P (ed) Improvement of Crop Plants for Industrial End Uses. Netherlands, Springer: 335–416.

Bryman A & Bell E (2007) Business research methods. 2nd edition. Oxford University Press.

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA & Marland G (2007) Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences 104(47): 18866–18870.

Chang C, Cen P & Ma X (2007) Levulinic acid production from wheat straw. Bioresource technology 98(7): 1448–1453.

Cheung H, Tanke R & Torrence GP (2000) Ullmann's Encyclopedia of Industrial Chemistry: Acetic Acid [Homepage of John Wiley & Sons, Inc.]. URI: http://mrw.interscience.wiley.com/emrw/9783527306732/ueic/article/a01_045/current/html#a01_045-sec1-0004. Cited 2010/07/07.

Childress Associates (2007) Gasification World Database (2007). Pittsburgh, U.S.Department of Energy, Office of Fossil Energy, National Energy Technology laboratory.

Commission of the European Communities (2007) Communication from the commission to the European Council and the European parliament. An energy police for Europe [Homepage of Commission of the European Communities]. URI: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0001:FIN:EN:PDF. Cited 2010/03/19.

Convery FJ & Redmont L (2007) Market and price developments in the European Union emissions trading scheme. Review of Environmental Economics and Policy 1(1): 88–111.

Corfee-Morlot J & Höhne N (2003) Climate change: long-term targets and short-term commitments* 1. Global Environmental Change 13(4): 277–293.

Corma A, Iborra S & Velty A (2007) Chemical routes for the transformation of biomass into chemicals. Chemical reviews 107(6): 2411–2502.

Council of Oulu Region (2007) Energy strategy for Northern Ostrobothnia (Finnish) [Homepage of Council of Oulu Region]. URI: http://www.pohjois-pohjanmaa.fi/maakunnan_suunnittelu_ja_kehittaminen/projektit/paattyneet/energiastrategia. Cited 2010/03/30.

Cox PM, Betts RA, Jones CD, Spall SA & Totterdell IJ (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408(6809): 184–187.

De Beer J, Worrell E & Blok K (1998) Future technologies for energy-efficient iron and steel making. Annual Review of Energy and the Environment 23(1): 123–205.

Demailly D & Quirion P (2008) European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry. Energy Economics 30(4): 2009–2027.

Demirbas A (2005) Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Progress in Energy and Combustion Science 31(2): 171–192.

Demirbas A (2004) Combustion characteristics of different biomass fuels. Progress in Energy and Combustion Science 30(2): 219–230.

Diemer P, Killich HJ, Knop K, Lüngen HB, Reinke M & Schmöle P (2004) Potentials for Utilization of Coke Oven Gas in Integrated Iron and Steel Works, 2nd International Meeting on Ironmaking/1st International Symposium on Iron Ore, Vitoria, Espirito Santo: 12.

Dincer I (2002) The role of exergy in energy policy making. Energy Policy 30(2): 137–149.

Domac J, Richards K & Risovic S (2005) Socio-economic drivers in implementing bioenergy projects. Biomass and Bioenergy 28(2): 97–106.

Eggert RG (2002) Mining and economic sustainability: National economies and local communities. Colorado, International institute for environment and development.

Einstein D, Worrell E & Khrushch M (2001) Steam systems in industry: Energy use and energy efficiency improvement potentials. Berkeley, Lawrence Berkeley National Laboratory.

Elghali L, Clift R, Sinclair P, Panoutsou C & Bauen A (2007) Developing a sustainability framework for the assessment of bioenergy systems. Energy Policy 35(12): 6075–6083.

Energy Information Administration. US Department of Energy. (1996) Growth of the landfill gas industry. URI: http://www.eia.doe.gov/cneaf/solar.renewables/renewable.energy.annual/chap10.html. Cited 2011/10/30

Energy Market Authority (2010) Emissions trading. URI: http://www.energiamarkkinavirasto.fi/select.asp?gid=199&languageid=246/. Cited 2010/03/22.

Enkvist P, Nauclér T & Rosander J (2007) A cost curve for greenhouse gas reduction. McKinsey Quarterly 1: 35–45.

Ericsson M (2010) Global Mining towards (2030). Espoo, Geological Survey of Finland.

Etelälahti P, Kangaspunta M & Wallin J (1992) Investointi- ja pääomakustannuslaskennan opas. Helsinki, Valtion Painatuskeskus.

EurObserv’er (2010) Biogas report. Paris, EurObserv'er.

European Climate Exchange (2010) ECX Historical Data. URI: http://www.ecx.eu/market-data/ecx-historical-data/. Cited 2010/09/17.

European Commission (2010) Emissions Trading System [Homepage of European Commission]. URI: http://ec.europa.eu/clima/policies/ets/index_en.htm. Cited 2011/06/06.

Evonik Industries (2010) Hydrogen Peroxide. URI: http://corporate.evonik.com/sites/dc/Downloadcenter/Evonik/Corporate/en/Investor-Relations/Portrait/Portraet_Wasserstoffperoxid_-_englisch.pdf/. Cited 2010/09/24.

Fiedler E, Grossmann G, Kersebohm DB, Weiss G, Witte C (2000) Methanol [Homepage of Wiley online library]. URI: http://onlinelibrary.wiley.com/doi/10.1002/14356007.a16_465/full. Cited 2010/09/23.

Finnish Government (2011) Emissions trade law (Finnish) 2011/311. URI: http://www.finlex.fi/. Cited 2011/10/13.

Finnish Government (2008) Long term climate and energy strategy (Finnish) [Homepage of Finnish Parliament]. URI: http://217.71.145.20/TRIPviewer/show.asp?tunniste=VNS+6/2008&base=ermuut&palvelin=www.eduskunta.fi&f=WORD. Cited 2010/03/29.

Finnish Government (2001) State subsidy for energy investments 2001/688. URI: http://www.finlex.fi/. Cited 2011/02/12.

Finnish Government (2000) Environmental protection law 2000/86. URI: http://www.finlex.fi/. Cited 2011/5/26.

Floren J (2010) Milestones-Methanol Institute. URI: http://www.methanol.org/pdfFrame.cfm?pdf=Milestones.pdf/. Cited 2010/09/23.

Flyktman M & Helynen S (2004) Quantification of efficiencies for the initial distribution of allowances in emissions trading. Jyväskylä, VTT. Research Report: PRO2/0071T/03.

Flyktman M, Kärki J, Hurskainen M, Helynen S & Sipilä K. (2011) Kivihiilen korvaaminen biomassoilla yhteistuotannon pölypolttokattiloissa. Helsinki, VTT Technical Research Centre of Finland.VTT Tiedotteita – research notes.

Fouquet D & Johansson TB (2008) European renewable energy policy at crossroads–Focus on electricity support mechanisms. Energy Policy 36(11): 4079–4092.

Frondel M, Schmidt CM & Vance C (2008) Emissions Trading: Impact on Electricity Prices and Energy-Intensive Industries. Bochum, Ruhr-Universität Bochum.

Frondel M, Ritter N, Schmidt CM & Vance C (2010) Economic impacts from the promotion of renewable energy technologies: The German experience. Energy Policy 38(8): 4048–4056.

Fuchs A, Moser MJ, Zangl H & Bretterklieber T (2009) Using Capacitive Sensing to Determine the Moisture Content of Wood Pellets–investigations and Application. International journal on smart sensing and intelligent systems 2(4): 293–308.

Gielen DJ & Van Dril AWN (1997) The Basic Metal Industry and Its Energy Use. Petten, Energy Research Centre of the Netherlands.

Goldemberg J & Teixeira Coelho. S (2004) Renewable energy—traditional biomass vs. modern biomass. Energy Policy 32(6): 711–714.

Goor G, Glenneberg J, Jacobi S (2007) Hydrogen Peroxide [Homepage of Wiley online library]. URI: http://onlinelibrary.wiley.com/doi/10.1002/14356007.a13_443.pub2/abstract. Cited 2010/09/23.

Grace J (2001) Carbon cycle. In Levin S (ed) Encyclopedia of biodiversity. San Diego, Academic Press: 609–628.

Graichen V, Schumacher K, Matthes FC, Mohr L, Duscha V, Schleich J & Diekmann J (2008) Impacts of the EU Emissions Trading Scheme on the industrial competitiveness in Germany. URI: http://www.umweltbundesamt.de. Cited 2011/7/6.

Green C & Byrne KA (2004) Biomass: Impact on Carbon Cycle and Greenhouse Gas Emissions. In Cleveland CJ (ed) Encyclopedia of Energy volume 1. Amsterdam, Academic Press: 223–236.

Green DW & Perry RH (2007) Perry's chemical Engineers' handbook. 8th edn. New York, McGraw-Hill Professional.

Greening LA, Greene DL & Difiglio C (2000) Energy efficiency and consumption — the rebound effect — a survey. Energy Policy 28(6–7): 389–401.

GTK, Geological Survey of Finland (2010) GTK. Natural resources. Metals. [Homepage of Geological Survey of Finland]. URI: http://www.gtk.fi/luonnonvarat2/metallit. Cited 2011/05/30.

Hahn H, Rurz D, Ferber E & Kirchmayer F (2010) Examples for financing of biogas projects in Germany, Austria, The Netherlands, Denmark and Italy. Brussels, European Biogas Association.

Harisalo R (2008) Organisaatioteoriat. Tampere, Tampere University Press.

Haszeldine RS (2009) Carbon capture and storage: how green can black be?, Science 325(5948): 1647–1652.

Haverila MJ, Uusi-Rauva E, Kouri I & Miettinen A. (2005) Teollisuustalous. 5th ed. Tampere, Tammer-Paino Oy.

Hayes DJ, Fitzpatrick S, Hayes MHB & Ross JRH (2006) The Biofine Process-Production of Levulinic Acid, Furfural, and Formic Acid from Lignocellulosic Feedstocks. Biorefineries: Industrial processes and products 1: 139–164.

Helynen S (2008) Energiatuotantoteknologiat ja tehostamismahdollisuudet. Asiantuntijaseminaari 12.2.2008: energiateknologia pitkän aikavälin ilmasto- ja energiastrategian politiikkaskenaariossa. URI: http://www.tem.fi/files/18689/Helynen_Energiantuotantoteknologiat.pdf. Cited 2010/03/11.

Hidalgo I, Szabo L, Carlos CJ & Soria A (2005) Technological prospects and CO2 emission trading analyses in the iron and steel industry: A global model. Energy 30(5): 583–610.

Higman C & Van der Burgt M (2003) Gasification. Burlington MA, Gulf Professional Publishing.

Hillebrandt K (2009) Drying and stocking of energy wood. Jyväskylä, VTT. Research Report: VTT-R-07261-09.

Hiremath RB, Kumar B, Balachandra P, Ravindranath NH & Raghunandan BN (2009) Decentralised renewable energy: Scope, relevance and applications in the Indian context. Energy for Sustainable Development 13(1): 4–10.

Hoffert MI, Caldeira K, Benford G, Criswell DR, Green C, Herzog H, Jain AK, Kheshgi HS, Lackner KS & Lewis JS (2002) Advanced technology paths to global climate stability: energy for a greenhouse planet. Science 298(5595): 981–987.

Holladay JD, Hu J, King DL & Wang Y (2009) An overview of hydrogen production technologies. Catalysis Today 139(4): 244–260.

Houghton JT, Ding Y, Griggs DJ, Noguer M, Linden van der PJ, Dai X, Maskell K & Johnson CA (2001) Climate change 2001: the scientific basis. Cambridge UK, Cambridge University Press.

Huber GW, Iborra S & Corma A (2006) Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering. Chemical Reviews-Columbus 106(9): 4044–4098.

Hydrocarbon Processing (1983) Formic acid – The Leonard Process Co. – Kemira Oy. Hydrocarbon processing 62(11): 104–104.

Icis.com (2009) Urea uses and market data. URI: http://www.icis.com/v2/chemicals/9076559/urea/uses.html/. Cited 2010/09/23.

International energy agency (2010) CO_2 emissions from fuel combustion highlights. Paris, OECD/IEA.

IPCC (2008) Climate Change 2007: Synthesis Report (Fourth assessment report of the IPCC) [Homepage of IPCC]. URI: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf. Cited 2010/07/08.

IPCC (2007) 2006 IPCC Guidelines for National Greenhouse Gas Inventories [Homepage of IPCC]. URI: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. Cited 2011/05/09.

Järvelä M, Jokinen P, Huttunen S & Puupponen A (2009) Local food and reneweable energy as emerging new alternatives of rural sustainability in Finland. European Countryside 1(2): 113–124.

Järvinen T, Malinen J, Tiitta M & Teppola P (2006) State of art – report of wood moisture measurement. Helsinki, VTT. Research Report: VTT-R-01325-07.

Jenck JF, Agterberg F & Droescher MJ (2004) Products and processes for a sustainable chemical industry: a review of achievements and prospects. Green Chemistry 6(11): 544–556.

Jenkins BM, Baxter LL, Miles TR & Miles TR (1998) Combustion properties of biomass. Fuel Processing Technology 54(1–3): 17–46.

Joseck F, Wang M & Wu Y (2008) Potential Energy and Greenhouse Gas Emission Effects of Hydrogen Production from Coke oven Gas in US Steel Mills. International Journal of Hydrogen Energy 33(4): 1445–1454.

Kaltschmitt M, Thrän D & Smith KR (2002) Renewable Energy from Biomass in Encyclopedia of Physical Sciences and Technology. 3rd edn. Burlington MA, Academic Press/Elsevier: 203–228.

Kamm B (2007) Production of platform chemicals and synthesis gas from biomass. Angewandte Chemie International Edition 46(27): 5056–5058.

Kara M, Syri S, Lehtilä A, Helynen S, Kekkonen V, Ruska M & Forsström J (2008) The impacts of EU CO2 emissions trading on electricity markets and electricity consumers in Finland. Energy Economics 30(2): 193–211.

Karjalainen T (2010) Bioenergy plan for Kainuu 2011–2015 (in Finnish). Kajaani, Centre for Economic Development, Transport and the Environment in Kainuu.

Kautto N, Arasto A, Sijm J & Peck P (2011) Interaction of the EU ETS and national climate policy instruments – Impact on biomass use. Biomass and Bioenergy. In Press, Corrected Proof.

Kemira Oyj (2008) Kemira increases formic acid capacity in Oulu [Homepage of Kemira Oyj]. URI: http://www.kemira.com/en/media/pressreleases/Pages/1238146_20080724100626.aspx. Cited 2010/01/19.

Kemira Oyj (2006) Kemira Annual Report 2005 [Homepage of Kemira Oyj]. URI: http://www.kemira.com/SiteCollectionDocuments/Media/Reports/Kemira_Annual_Report_2005.pdf. Cited 2010/01/19.

Khan AA, de Jong W, Jansens PJ & Spliethoff H (2009) Biomass combustion in fluidized bed boilers: Potential problems and remedies. Fuel Processing Technology 90(1): 21–50.

Kim Y & Worrell E (2002) International comparison of CO2 emission trends in the iron and steel industry. Energy Policy 30(10): 827–838.

Kirkinen J (2010) Greenhouse impact assessment of some combustible fuels with a dynamic life cycle approach. Dissertation Thesis, Åbo Akademi university. VTT Publications 733.

Koljonen T & Savolainen I (2005) Impact of the eu emissions trading directive on the energy and steel industries in Finland. In Rubin ES, Keith DW, Gilboy CF, *et al.* (eds) Greenhouse Gas Control Technologies 7. Oxford, Elsevier Science: 833–840.

Korpilahti A & Melkas T (2010) Online measurement of moisture of logging waste chips. Helsinki, Metsäteho Oy.

Kossoy A & Ambrosi B (2010) State and trends of the carbon markets (2010). Washington DC, The World Bank.

Kuittinen V, Huttunen MJ & Leinonen S (2010) Register of Finland's biogas installations (in Finnish). Joensuu, University of eastern Finland. Register of Finland's biogas installations no 13.

Kurkela E (2009) Biomass gasification technologies for advanced power systems and synfuels – Status and Present R&D activities in Finland. Finnish-Swedish flame days. Naantali, Finland: 1–18.

Kurkela E (2002) Rewiev of Finnish biomass gasification technologies. Espoo, VTT. OPET Report 4.

Lancaster G (2005) Research Methods in Management: A concise introduction to research in management and business consultancy. Oxford, Butterworth-Heinemann.

Launonen U & Stenlund H (2009) Optimised Biofuel Management with the New Generation of Moisture Meter. 63rd Appita Annual Conference and Exhibition, Melbourne 19–22 April 2009: 407.

Lee JS, Kim J & Kim Y (1990) Methyl formate as a new building block in C1 chemistry. Applied Catalysis 57(1): 1–30.

Lehtomäki A (2006) Biogas production from energy crops and crop residues. Dissertation Thesis. Jyväskylä, University of Jyväskylä. Jyväskylä studies in biological and environmental science 163.

Lenzen M & Murray S (2001) A modified ecological footprint method and its application to Australia. Ecological Economics 37(2): 229–255.

Leonard JD (1979) Preparation of formic acid by hydrolysis of methyl formate, EP5998 edn, C07C53/02, C07C51/09, C07C27/02, EU.

Machida S, Akiyama T, Muramatsu A & Yagi J (1997) Direct Conversion of Blast Furnace Gas to Dimethyl Ether over Cu-ZnO-Ga 2 O 3/γ-Al 2 O 3 Hybrid Catalyst: Optimum Mass Ratio of the Catalyst. ISIJ International 37(5): 531–535.

Marsella J (1994) Formic acid and derivatives. In Kroschwitz JI (ed) Kirk-Othmer encyclopedia of chemical technology. 4th edn. New York, John Wiley & Sons: 967–976.

McKendry P (2002) Energy production from biomass (part 1): overview of biomass. Bioresource technology 83(1): 37–46.

Meessen JH & Petersen H (2000) Urea [Homepage of Wiley online library]. URI: http://onlinelibrary.wiley.com.pc124152.oulu.fi:8080/doi/10.1002/14356007.a27_333/full. Cited 2010/09/23.

Metz B, Davidson O, de Coninck HC, Loos M & Meyer LA (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge, Cambridge University Press.

Miles L & Kapos V (2008) Reducing greenhouse gas emissions from deforestation and forest degradation: global land-use implications. Science 320(5882): 1454–1455.

Mining-technology.com (2010) Talvivaara Bioheapleach, Finland [Homepage of Mining-technology.com]. URI: http://www.mining-technology.com/projects/category/. Cited 2011/05/23.

Ministry of employment and the economy (2010) Uusiutuvan energian velvoitepaketti (Commitments to renewable enegy). URI: http://www.tem.fi/files/26643/UE_lo_velvoitepaketti_Kesaranta_200410.pdf. Cited 2011/02/12.

Monni S (2010) Greenhouse gas balance in Kainuu (Finnish). Espoo, Benviroc Oy.

Moreno B & Lopez AJ (2008) The effect of renewable energy on employment. The case of Asturias (Spain). Renewable and Sustainable Energy Reviews 12(3): 732–751.

Murphy JD & Power N (2009) Technical and economic analysis of biogas production in Ireland utilising three different crop rotations. Applied Energy 86(1): 25–36.

National Audit Office of Finland (2009) Päästökauppa – Kioton joustomekanismit. Helsinki, Valtion tarkastusviraston tuloksellisuustarkastuskertomukset 200/2009.

Neste Oil (2010) Price of propane. Oulu, Finland, Neste Oil.

Neuhoff K, Keats K & Sato M (2006) Allocation, incentives and distortions: the impact of EU ETS emissions allowance allocations to the electricity sector [Homepage of Faculty of Economics, University of Cambridge, UK]. URI: http://www.dspace.cam.ac.uk/bitstream/1810/183627/1/eprg0618.pdf. Cited 2010/08/23.

Nord Pool (2010) Market Prices [Homepage of Nord Pool ASA]. URI: http://www.nordpool.com/trading/marketprices/history/. Cited 2010/09/27.

Nykänen J, Roglieri M & Voogt M (2006) Velvoitepohjaiset päästökauppajärjestelmät. In: Nykänen J (ed) Päästökauppa ja ympäristöhyödykkeiden markkinat. Helsinki, Edita publishing Oy: 51–75.

Paappanen T, Lindh T, Kärki J, Impola R & Rinne S (2008) Reed canary grass production- and supply chain and usage as fuel in boiler houses (in Finnish). Maataloustieteen päivät 2008, The Finnish Society of Agronomy.

Paavola T (2007) Biogas seminar – raw materials, efficiency, handling and process (in Finnish) [Homepage of Cropgen research project (EU's 6th Framework Programme)]. URI: http://www.cropgen.soton.ac.uk/publications/8%20Other/Oth_35_Biogas%20seminar_Paavola.pdf. Cited 2011/02/12.

Pacala S & Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305(5686): 968–972.

Pahkala K, Aalto M, Isolahti M, Poikola J & Jauhiainen L (2008) Large-scale energy grass farming for power plants–A case study from Ostrobothnia, Finland. Biomass and Bioenergy 32(11): 1009–1015.

Persson M (2003) Evaluation of upgrading techniques for biogas. Lund, School of Environmental Engineering Lund University.

Pielke R, Wigley T & Green C (2008) Dangerous assumptions. Nature 452(7187): 531–532.

Pimentel D (2001) Biomass utilization, Limits of. In Meyers RA (ed) Encyclopedia of Physical Science and Technology. Third Edition. San Diego, Academic Press: 159–171.

Ranta T, Lahtinen P, Elo J & Laitila J (2007) The effect of CO2 emission trade on the wood fuel market in Finland. Biomass and Bioenergy 31(8): 535–542.

Ranta T & Rinne S (2006) The profitability of transporting uncomminuted raw materials in Finland. Biomass and Bioenergy 30(3): 231–237.

Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG, Klepper G & Field CB (2007) Global and regional drivers of accelerating CO2 emissions. Proceedings of the National Academy of Sciences 104(24): 10288.

Reijnders L (2006) Conditions for the sustainability of biomass based fuel use. Energy Policy 34(7): 863–876.

Reutemann W & Kieczka H (2000) 15.6.2000-last update, Formic Acid: Ullmann's Encyclopedia of Industrial Chemistry [Homepage of John Wiley & Sons, Inc.]. URI: http://mrw.interscience.wiley.com.pc124152.oulu.fi:8080/emrw/9783527306732/ueic/article/a12_13/current/html. Cited 2010/03/31.

Rochelle GT (2009) Amine scrubbing for CO2 capture. Science 325(5948): 1652–1654.

Röser D, Erkkilä A, Mola-Yudego B, Sikanen L, Prinz R, Heikkinen A, Kaipainen H, Oravainen H, Hillebrand K, Emer B & Väätäinen K (2010) Natural drying methods to promote fuel quality enhancement of small energywood stems, Metla, Vantaa, Working papers of the Finnish Forest Research Institute 186.

Rostrup-Nielsen JR (2002) Syngas in perspective. Catalysis Today 71(3–4): 243–247.

Rostrup-Nielsen JR (2000) New aspects of syngas production and use. Catalysis today 63(2–4): 159–164.

Rydin Y, Holman N & Wolff E (2003) Local sustainability indicators. Local Environment 8(6): 581–589.

Saikku L, Rautiainen A & Kauppi P (2008) The sustainability challenge of meeting carbon dioxide targets in Europe by 2020. Energy Policy 36(2): 730–742.

Salmi O (2007) Eco-efficiency and industrial symbiosis–a counterfactual analysis of a mining community. Journal of Cleaner Production 15(17): 1696–1705.

Saunders M, Lewis P & Thornhill A (2007) Research methods for Business Students. 4th edition. Prentice Hall.

Schmalensee R, Stoker TM & Judson RA (1998) World carbon dioxide emissions: 1950–2050. Review of Economics and Statistics 80(1): 15–27.

Scott E, Peter F & Sanders J (2007) Biomass in the manufacture of industrial products—the use of proteins and amino acids. Applied Microbiology and Biotechnology 75(4): 751–762.

Seppälä J, Koskela S, Melanen M & Palperi M (2002) The Finnish metals industry and the environment. Resources, Conservation and Recycling 35(1–2): 61–76.

Seppälä M, Paavola T, Lehtomäki A & Rintala J (2009) Biogas production from boreal herbaceous grasses – Specific methane yield and methane yield per hectare. Bioresource technology 100(12): 2952–2958.

Shu-Ren H (1998) Hydrocarbon steam-reforming process: Feedstock and catalysts for hydrogen production in China. International Journal of Hydrogen Energy 23(5): 315–319.

Sijm J, Hers SJ, Lise W & Wetzelaer B (2008) The impact of the EU ETS on electricity prices. Energy research centre of the Netherlands.

Sikanen L (2009) The significance of moisture in the forest industry supply chain. Joensuu, University of Joensuu. Metsäenergia-Foorumi. 10.6.2009 Joensuu.

Smyth BM, Smyth H & Murphy JD (2010) Can grass biomethane be an economically viable biofuel for the farmer and the consumer?, Biofuels, Bioproducts and Biorefining 4(5): 519–537.

Solomon S, Plattner GK, Knutti R & Friedlingstein P (2009) Irreversible climate change due to carbon dioxide emissions., Proceedings of the National Academy of Sciences 106(6): 1704–1709.

Song C (2006) Global challenges and strategies for control, conversion and utilization of CO2 for sustainable development involving energy, catalysis, adsorption and chemical processing. Catalysis Today 115(1–4): 2–32.

Statistics Finland (2011) Greenhouse gas emissions in Finland 1990–2009 Helsinki. Statistics Finland.

Statistics Finland (2010) Energy sourcing, consumption and prices (in Finnish) [Homepage of Statistics Finland]. URI: http://www.stat.fi.pc124152.oulu.fi:8080/til/ehkh/2010/03/ehkh_2010_03_2010-12-16_fi.pdf. Cited 2011/02/22.

Steinfeld H, Gerber P, Wassenaar T, Castel V & de Haan C (2006) Livestock's long shadow: environmental issues and options. Rome, FAO.

Stern NH (2007) The economics of climate change: the Stern review. Cambridge, Cambridge Univ Pr.

Stickland LH (1929) The bacterial decomposition of formic acid. Biochemical Journal 23(6): 1187.

Stora Enso (2009) Stora Enso and Neste biofuels inaugurate demonstration facility at Varkaus in Finland [Homepage of Stora Enso]. URI: http://www.storaenso.com/media-centre/press-releases/2009/06/Pages/stora-enso-and-neste-oil.aspx. Cited 2010/03/24.

Sukumaran Nair MP (2006) Ammonia industry – today and tomorrow. Hydrocarbon Processing 85(4): 47–55.

Sundarakani B, de Souza R, Goh M, Wagner SM & Manikandan S (2010) Modeling carbon footprints across the supply chain. International Journal of Production Economics 128(1): 43–50.

Talvivaara Oyj (2009) Production process [Homepage of Talvivaara Oyj]. URI: http://www.talvivaara.com/toiminta/_toiminta/tuotantoprosessi. Cited 2011/05/23.

Teir S, Tsupari E, Arasto A, Koljonen T, Kärki J, Lehtilä A, Kujanpää L, Aatos S & Nieminen M (2011) Prospects for application of CCS in Finland. Energy Procedia 4: 6174–6181.

Tekes (2011) Tekes launches a Green Mining programme [Homepage of Tekes]. URI: http://www.tekes.fi/fi/community/Uutiset/404/Uutinen/1325?name=tekes+kaynnistaa+green+mining+ohjelman. Cited 2011/05/23.

Tekes (2010) Customer results. Talvivaara Mining Oyj. [Homepage of Tekes]. URI: http://www.tekes.fi/fi/community/Asiakkaiden_tuloksia/403/Asiakkaiden_tuloksia/647?name=Riskinotto+kannatti. Cited 2011/05/23.

The Environmental Centre of Northern Ostrobothnia (2007a), Environmental permission for production of chemicals, PPO-2005-Y-1-111.

The Environmental Centre of Northern Ostrobothnia (2007b) Environmental permission for boiler house, PPO-2005-Y-1-111.

The European parliament (2009) Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

The European Parliament (2003) Directive 2003/87/EC.

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, De Siqueira MF, Grainger A & Hannah L (2004) Extinction risk from climate change. Nature 427(6970): 145–148.

Thomson Reuters (2010) 1.4.2010-last update, POLL EU carbon emissions, EUA price forecasts to 2020 [Homepage of Reuters News]. URI: http://communities.thomsonreuters.com/Carbon/507401. Cited 2010/05/04.

Tietenberg T (2010) The Evolution of Emissions Trading. In: Siegfried JJ (ed) Better living through Economics. Library of Congress USA, Harvard University Press: 42–62.

Turpeinen E, Raudaskoski R, Pongrácz E & Keiski RL (2008) Thermodynamic analysis of conversion of alternative hydrocarbon-based feedstocks to hydrogen. International Journal of Hydrogen Energy 33(22): 6635–6643.

Tuusjärvi M, Sarapää O, Tontti M, Ahtola T, Kinnunen K, Luodes H, Hyvärinen J, Virtanen K, Kallio J & Vuori S (2010) Utilization of geolocigal resources in Finland in 2009 (in Finnish). Espoo, GTK.

Uhde Technologies (2010) 22.3.2010-last update, The Shell Gasification Process [Homepage of Uhde GmbH]. URI: http://www.uhde.eu/cgi-bin/byteserver.pl/pdf/broschueren/Oil_Gas_Refinery/Shell_Gasification_Process.pdf. Cited 2010/08/03.

Unander F, Karbuz S, Schipper L, Khrushch M & Ting M (1999) Manufacturing energy use in OECD countries: decomposition of long-term trends. Energy Policy 27(13): 769–778.

United Nations (1997) Kyoto protocol to the United Nations framework convention on climate change [Homepage of United Nations]. URI: http://unfccc.int/kyoto_protocol/items/2830.php. Cited 2010/03/19.

UPM (2007) UPM and Andritz-Carbona team up for biomass based synthetic gas production [Homepage of UPM]. URI: http://w3.upm-kymmene.com/upm/internet/cms/upmcms.nsf/($all)/3ed4d077ffc471b1c22572e4002de186?OpenDocument&qm=menu,0,0,9. Cited 2010/04/05.

Uusisuo M (2010) Mining. Report. [Homepage of Ministry of employment and the economy]. URI: http://www.temtoimialapalvelu.fi/files/1110/Kaivosala_2010_web.pdf. Cited 2011/05/23.

Van der Drift A & Boerrigter H (2006) Synthesis gas from biomass for fuels and chemicals. SYNBIOS Conf. Stockholm, Sweden. May 2005.

Van der Zwaan B (2008) Prospects for nuclear energy in Europe. International Journal of Global Energy Issues 30(1): 102–121.

Vörösmarty CJ, Green P, Salisbury J & Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Science 289(5477): 284–288.

Wackernagel M (1998) The ecological footprint of Santiago de Chile. Local Environment 3(1): 7–25.

Wei M, Patadia S & Kammen DM (2010) Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US?, Energy Policy 38(2): 919–931.

Weiland P (2010) Biogas production: current state and perspectives. Applied Microbiology and Biotechnology 85(4): 849–860.

Weiland P (2003) Production and energetic use of biogas from energy crops and wastes in Germany. Applied Biochemistry and Biotechnology 109(1): 263–274.

Weinstock B (1969) Carbon monoxide: Residence Time in the Atmosphere. Science 166(902): 224–225.

Weltec Biopower (2010) Weltec Biogaspark mit Gaseinspeisung [Homepage of Weltec Biopower GmbH]. URI: http://www.weltec-biopower.de/Biogaspark-Koennern.300.0.html. Cited 2011/02/22.

White DS & Sulkowski AJ (2010) Relative ecological footprints based on resource usage efficiency per capita: macro-level segmentation of 121 countries. International Journal of Sustainable Economy 2(2): 224–240.

Wiedmann T & Minx J (2007) A definition of 'Carbon Footprint'. Durham, ISAUK Research & Consulting.

Wilhelm DJ, Simbeck DR, Karp AD & Dickenson RL (2001) Syngas production for gas-to-liquids applications: technologies, issues and outlook* 1. Fuel Processing Technology 71(1–3): 139–148.

World steel association (2009) World steel in figures 2009. Brussels, World steel association, 2009 edition.

Worrell E, Phylipsen D, Einstein D & Martin N (2000) Energy use and energy intensity of the US chemical industry. Berkeley, University of California.

Worrell E, Price L, Martin N, Hendriks C & Meida LO (2001) Carbon Dioxide Emissions from the Global Cement Industry 1. Annual Review of Energy and the Environment 26(1): 303–329.

Xu C & Cang D (2010) A Brief Overview of Low CO2 Emission Technologies for Iron and Steel Making. Journal of Iron and Steel Research, International 17(3): 1–7.

Yali L (2006) Formic Acid Market. China Chemical Reporter 17(17): 15–15.

Original publications

I Arvola J, Belt P, Harkönen J & Möttönen M (2011) Replacing fossil raw materials by using renewable sources in Northern Finland. 2nd International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS2), 19–21 June, 2011, Nisyros – Greece.

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