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Impact of system boundaries on the effectiveness of climate change mitigation actions

Eemeli Tsupari

Aalto University

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Eemeli Tsupari

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Abstract

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Abstract

Despite international agreements, global greenhouse gas (GHG) emissions have not decreased according to the targets. Consequently, our generation is creating an enormous problem for future generations. As climate change is a global problem, GHG emissions must decrease globally. Consequently, international policies are needed, actions should be effective and the impacts should be assessed with broad boundaries.

In Europe, the cornerstone of climate policy is the EU Emissions Trading Scheme (EU ETS) but the rebound impacts within the EU ETS are often excluded in the assessments. This dissertation examines the impacts of major CO_2 emission reduction solutions with different system boundaries, highlighting the importance of boundary selection on the results. In addition, the economic feasibilities of the selected solutions are evaluated.

The case examples represent the most important sectors in terms of global CO_2 emissions, such as electricity and heat production, the steel industry and transport. The studied technologies include efficient Waste-to-Energy (WtE) concepts with high power-to-heat ratio, utilisation of CO_2 Capture and Storage (CCS) in different applications, replacing steel mill blast furnaces with Oxygen Blast Furnaces (OBF), Combined Heat and Power (CHP) and Carbon Capture and Utilisation (CCU) for storable fuels, which can be used for example in transportation.

The results highlight the importance of the consequences in the electricity production system as well as the rebound impacts in the EU ETS. For example, the studied concepts to decrease direct GHG emissions of steel mills lead to increased power purchase from markets and consequently increase in emissions of the power system. The impacts of CCU concepts based on electrolysis increase the emissions in electricity production but enable a decrease in the usage of fossil fuels in transportation. In addition, converting electricity to storable fuels enable higher shares of variable solar and wind energy in the power systems.

The consequences in the power systems are complex, including for example the impacts on electricity imports and exports, future investments and the EU ETS. Even if these impacts can be recognised by qualitative means, unambiguous quantitative consequences cannot be given. Understanding the decisive impacts of the framework and boundaries is crucial to interpreting different assessments and making effective actions and policy decisions. Solutions which decrease emissions within a narrow system boundary can actually increase the emissions of the broader system.

Keywords Climate change mitigation, greenhouse gases, carbon dioxide, emissions trading, economic feasibility

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Tiivistelmä

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Tiivistelmä
Kansainvälisistä sopimuksista huolimatta globaaleja kasvihuonekaasupäästöjä ei ole saatu vähennettyä ja sukupolvemme on jättämässä perinnöksi tuleville sukupolville valtavan haitan. Globaalina ongelmana ilmastonmuutos vaatii laajoja kansainvälisiä sopimuksia ja laaja-alaisesti vaikuttavia keinoja.
Euroopassa keskeisin ilmastopoliittinen ohjauskeino on EU:n laajuinen päästökauppa (EU ETS), jonka merkitys on kuitenkin usein unohdettu tarkasteltaessa toimenpiteiden ilmastovaikutuksia. Tässä väitöskirjassa tarkastellaan eräiden päästövähennysratkaisujen vaikutuksia esimerkkitapauksissa erilaisilla järjestelmärajauksilla, jolloin rajausten ratkaiseva merkitys näkyy tuloksissa. Lisäksi arvioidaan päästövähennysten taloudellista kannattavuutta.
Esimerkkitapaukset edustavat globaalien hiilidioksidipäästöjen kannalta tärkeimpiä sektoreita kuten sähkön ja lämmön tuotantoa, terästeollisuutta ja liikennettä. Tarkastellut teknologiset ratkaisut sisältävät tehokkaita korkean rakennusasteen jätteenpolttoratkaisuja, hiilidioksidin talteenottoa ja varastointia (CCS) eri sovelluskohteissa, terästehtaan masuunien korvaamista happimasuuneilla, sähkön ja lämmön yhteistuotantoa (CHP) eri polttoaineilla sekä hiilidioksidin hyötykäyttöä (CCU) esimerkiksi liikennepolttoaineiksi.
Tuloksissa korostuvat erityisesti vaikutukset sähköjärjestelmään sekä EU ETS:n takaisinkytkentöjen merkitys. Esimerkiksi tarkastellut terästehtaan ratkaisut vähentävät merkittävästi tehtaan suoria päästöjä, mutta kasvattavat sähkön hankintaa verkosta lisäten päästöjä sähkön tuotantojärjestelmässä. Samankaltaisia vaikutuksia seuraa elektrolyysiin perustuvista CCU-ratkaisuista, joiden avulla kuitenkin voidaan vähentää fossiilisten polttoaineiden käyttöä esimerkiksi liikenteessä sekä lisätä vaihtelevan uusiutuvan energian (aurinko- ja tuulivoima) osuutta energiajärjestelmissä.
Vaikutukset sähköntuotantojärjestelmään ovat erittäin moniulotteisia, sisältäen mm. vaikutuksia sähkön tuontiin ja vientiin, tulevaisuuden investointeihin ja päästökauppaan. Kaikkia vaikutuksia ei ole mahdollista yksiselitteisesti huomioida tarkasteltavien toimenpiteiden ilmastovaikutuksissa. Toimintaympäristön sekä rajausten ratkaisevan vaikutuksen ymmärtäminen on keskeistä erilaisten tarkastelujen tulkitsemiseksi sekä tehokkaiden toimien ja poliittisten päätösten tekemiseksi. Ratkaisut, jotka vähentävät päästöjä kapealla tarkastelurajauksella saattavat todellisuudessa lisätäkin päästöjä laajemmassa järjestelmässä.

Avainsanat Ilmastonmuutos, kasvihuonekaasut, hiilidioksidi, ilmastonmuutoksen hillintä, päästökauppa, kustannukset

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Preface and acknowledgements

After my graduation with a Master's of Science degree in 2005, I did not aim to continue for a Doctor's degree. However, the research topics at VTT were interesting and with several brilliant co-authors, we published scientific articles in high-level journals. I was repeatedly encouraged to compile these articles into a dissertation, for which I am certainly grateful to Prof. Peter Lund, Prof. Ilkka Savolainen, Prof. Sanna Syri, Dr. Petteri Laaksonen, and Dr. Sari Siitonen. In spring 2017, I decided to apply a scholarship from Fortum Foundation to compile a thesis. The six month scholarship helped me to finish the thesis, for which I express my greatest gratitude to Fortum Foundation.

I kindly thank all organizations that have funded my work. I want to acknowledge especially Tekes (currently Business Finland) for the majority of the funding via several projects and programmes. I also thank VTT, Statistics Finland, Association of Finnish Energy Industries, Finnish Forest Industries Federation, Ministry of Trade and Industry, Ministry of Environment, Foster Wheeler, Metso (Kvaerner Power), Bioenergy NoE, the Graduate School in Chemical Engineering, CLIC Innovation (CLEEN), Geological Survey of Finland, Fortum, Pohjolan Voima, SSAB (Ruukki), Vapo and Helen for funding the research included in this dissertation.

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Finally I thank my beloved children Lilja, Heljä and Leo. You, and your foreseen children, are the main motivation for me to keep on working with this difficult topic.

Jyväskylä, December 2018
Eemeli Tsupari

List of publications

This thesis is based on the following original publications, which are referred to in the text as I–VI. The publications are reproduced with kind permission from the publishers.

I Tsupari, Eemeli; Monni, Suvi; Tormonen, Kauko; Pellikka, Tuula; Syri, Sanna. 2007. Estimation of annual CH_4 and N_2O emissions from fluidised bed combustion: An advanced measurement-based method and its application to Finland. Elsevier Ltd. International Journal of Greenhouse Gas Control, volume 1, No. 3, July, pages 289 - 297. ISSN 1750-5836. DOI:10.1016/S1750-5836(07)00019-9

II Vainikka, Pasi; Tsupari, Eemeli; Sipilä, Kai; Hupa, Mikko. 2012. Comparing the greenhouse gas emissions from three alternative waste combustion concepts. Elsevier Ltd. Waste Management, volume 32, No. 3, March, pages 426-437. ISSN 0956-053X. DOI:10.1016/j.wasman.2011.10.010

III Tsupari, Eemeli; Kärki, Janne; Arasto, Antti; Pisilä, Erkki. 2013. Post-combustion capture of CO_2 at an integrated steel mill - Part II: Economic feasibility. Elsevier Ltd. International Journal of Greenhouse Gas Control, volume 16, August, pages 278 - 286. ISSN 1750-5836. DOI:10.1016/j.ijggc.2012.08.017

IV Tsupari, Eemeli; Kärki, Janne; Arasto, Antti; Lilja, Jarmo; Kinnunen, Kimmo; Sihvonen, Miika. 2015. Oxygen blast furnace with CO_2 capture and storage at an integrated steel mill. Part II: Economic feasibility in comparison with conventional blast furnace highlighting sensitivities. Elsevier Ltd. International Journal of Greenhouse Gas Control, volume 32, January, pages 189 - 196. ISSN 1750-5836. DOI:10.1016/j.ijggc.2014.11.007

V Tsupari, Eemeli; Kärki, Janne; Vakkilainen, Esa. 2016. Economic feasibility of power-to-gas integrated with biomass fired CHP plant. Elsevier Ltd. Journal of Energy Storage, volume 5, February, pages 62-69. ISSN 2352-152X. DOI:10.1016/j.est.2015.11.010

VI Tsupari, Eemeli; Arponen, Timo; Hankalin, Ville; Kärki, Janne; Kouri, Sampo. 2017. Feasibility comparison of bioenergy and CO_2 capture and storage in a large combined heat, power and cooling system. Elsevier Ltd. Energy, volume 139, November, pages 1040-1051. ISSN 0360-5442. DOI:10.1016/j.energy.2017.08.022

Author's contributions

Publication I: The disputant developed the method to apply measurement results to national emission factors with the other authors. He made the majority of the analyses on the basis of the measurements made by the project group. He was the corresponding author of the Publication.

Publication II: The disputant defined the approaches and system boundaries for calculating impacts on greenhouse gas emissions. The disputant performed the majority of the calculations and sensitivity analyses on the basis of the concepts and process parameters defined by Pasi Vainikka, who was the corresponding author of the Publication

Publication III: The disputant conducted the economic calculations and analysed the impacts on CO_2 emissions together with the other authors. He was the corresponding author of the Publication.

Publication IV: The disputant developed the methodology to compare the economic feasibility of the studied concepts. He conducted the majority of the economic calculations with Janne Kärki and analysed the impacts on CO_2 emissions based on the process modelling conducted by Antti Arasto. He was the corresponding author of the publication.

Publication V: The disputant created the model to estimate economic feasibility of the studied concept with Janne Kärki. The disputant conducted the economic calculations and analysed the impacts on CO_2 emissions. He was the corresponding author of the publication.

Publication VI: The disputant designed the system model with Timo Arponen and Janne Kärki. The disputant created an Excel tool to calculate the CO_2 emissions and economic feasibility of the studied concepts. He was the corresponding author of the publication.

Contents

List of abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business-As-Usual
BFB	Bubbling Fluidised Bed
bio-CCS	Capture and Storage of biogenic CO_2
CAPEX	Capital Expenditure
CCS	CO_2 Capture and Storage
CCS/U	CO_2 Capture and Storage/Utilisation
CCU	Carbon Capture and Utilisation
CFB	Circulating Fluidised Bed
CH_4	Methane
CHP	Combined Heat and Power
CHPC	Combined Heating, Power and Cooling
CO_2	Carbon dioxide
COP	Coefficient of Performance
EF	Emission Factor
EU	European Union
EU ETS	EU Emissions Trading Scheme (a.k.a. Emissions Trading System)
FCR	Frequency Containment Reserves
GHG	Greenhouse Gas
GTCC	Gas Turbine Combined Cycle
HOB	Heat Only Boiler
IPCC	Intergovernmental Panel on Climate Change

ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MEA	Monoethanolamine
MRR	Monitoring and reporting regulation of the EU ETS
MSR	Market Stability Reserve
MSW	Municipal Solid Waste
N_2O	Nitrous oxide (aka dinitrogen monoxide or laughing gas)
non-ETS	Sectors not covered by the EU ETS
NO_x	Nitrogen Oxides
OBF	Oxygen Blast Furnace
OPEX	Operational Expenditures
PtF	Power-to-Fuels
PtG	Power-to-Gas
PV	Photovoltaic
SNG	Synthetic Natural Gas
SO_x	Sulphur Oxides
SRF	Solid Residue Fuel
TGRBF	Top Gas Recycling Blast Furnace
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital
WtE	Waste-to-Energy

1. Introduction

Because of the global nature of climate change, it is essential to decrease greenhouse gas (GHG) emissions on a global level. This means that the advantage of any action reducing GHG emissions somewhere is diminished if it leads to increase of emissions elsewhere on the globe. It is difficult to evaluate the possible consequences of actions on a global level, because the impacted systems tend to become extremely complex and the results sensitive to the assumptions. Therefore, numerous possible consequences need to be excluded from the assessments even if the selected boundaries and limitations are not always presented.

An example of a narrow system boundary is to consider only the direct emissions of the studied plant, i.e. the physical flow of emissions from the plant. A bit broader system boundary can be for example the district heating system of a city, in which several combustion plants are connected to the same district heating network. In such a system, changes enacted in one plant may affect the operation and consequently emissions in other plants as well. Furthermore, a broader system can be an electricity system connected by a grid, or limited to a common market place. In such a system, the actions in one plant, which impact on the electricity consumption, production and/or price, have consequences for the other plants and emissions connected to the same grid. However, the considered systems and impacts can also be extended on other dimensions. These can include for example time, available resources, prices, investments and future decisions.

In the worst case, slightly different selections in boundary setting lead to opposite results. This is actually common in the case of concepts resulting in large changes in electricity consumption or production. In these cases, the importance of the consequences assumed to occur in the power system are emphasised. In addition, if the fixed cap of the European Union's Emissions Trading Scheme (EU ETS, a.k.a. EU Emissions Trading System) is considered, the studied operation may decrease the demand of emission allowances in the plant included in the EU ETS but increase GHG emissions in a non-ETS sector or outside the European Union (EU). In these cases, the emission allowances of EU ETS are released for markets and will be used by some other operator in the EU ETS. Consequently, CO_2 emissions are not decreased in the EU ETS but are increased in the non-ETS sector or outside the EU. This kind of impacts can be called *carbon leakage*, which is commonly used in discussions concerning the risks of potential carbon leakages from the EU to countries with laxer GHG emission constraints (EC, 2017). Taking into account the fixed cap of EU ETS highlights the importance of avoiding carbon leakages from the EU ETS sector to others.

Too narrow system boundaries often lead to misleading results. Unprofessional interpretation of these results may lead to ineffective and therefore expensive climate change mitigation actions, regulations or policies. The functioning of the EU ETS has been criticised due to the low price of the emissions allowance during the current decade (EEX, 2018), and overlapping national and regional policies have been created. The low price is due to the surplus of emission allowances, which means that the CO_2 emissions have decreased more than anticipated when the reduction targets of the EU ETS were set (EC, 2017). The surplus of allowances is largely due to the economic crisis in Europe since 2009 and high imports of international emission reduction credits into the system (ibid.). The long economic down-term in Europe decreased the price of emission allowance, because it decreased industrial production and consequently industrial CO_2 emissions and consumption of CO_2 allowances, leading to a surplus of allowances.

Although the rebound impacts have often been excluded or even ignored in studies assessing impacts on GHG emissions, since 2005 EU ETS has been a cornerstone for reaching the GHG targets in Europe (ibid.). The rebound impact on available allowances is so clear and important that it is essential to take this into account in the GHG impact assessments dealing with EU ETS.

This dissertation highlights the impacts of the selected system boundaries on the results of studies dealing with the effectiveness of climate change mitigation actions. The aim of the study is to increase awareness of the decisive impacts of the boundary selections using the selected concept studies as examples. The importance of the EU ETS is emphasised and the economic feasibilities of the studied concepts are evaluated against the prices of CO_2 emission allowances in the EU ETS.

1.1 Objective and scope

Climate change mitigation requires effective and truly additional actions, which should decrease GHG emissions globally. Numerous technology concepts for large GHG reductions are available, but the effectiveness of these concepts in climate change mitigation is strongly dependent on the boundaries selected for the impact assessments. The objective of this dissertation is to answer the following research questions.

- What are the impacts of the investigated technology concepts on direct GHG emissions from the studied plants?
- What kind of impacts do these investigated concepts have on the connected electricity and heating systems, and consequently on system level GHG emissions?
- How do the impacts on GHG emissions change when few important factors and boundaries are taken into account?
- What is the economic feasibility of the studied concepts from the operator’s point of view?

The benefits of achieved reductions in direct GHG emissions may be diminished by the system level consequences. Understanding the consequences in broad systems is important in the battle against a global problem such as climate change. However, the impacts in broad systems cannot be managed by a single actor, and thus cannot be unambiguously accounted for a single operator nor operation. In addition, the uncertainties in the system level assessments are an order of magnitude greater than in the case of direct emissions.

This dissertation is a summary of six peer-reviewed articles published in four different scientific journals between 2007 and 2017. In these articles, the studied concepts to reduce GHG emissions are evaluated with different system boundaries. The studied concepts include example solutions to many of the most important sectors in terms of global GHG emissions, namely production of heat and electricity, transportation, waste management and steel production. The studied concepts are:

1. Waste-to-energy (WtE) with increased power-to-heat ratio based on bubbling fluidised bed (BFB) combustion of waste and injection of chemical additives (Publication II)
2. WtE with increased power-to-heat ratio based on circulating fluidised bed (CFB) co-firing of waste and high ash coal (Publication II)
3. Post-combustion CO_2 Capture and Storage (CCS) in a blast furnace-based steel mill (Publication III)
4. Oxygen blast furnace (OBF) in a steel mill (Publication IV)
5. OBF in a steel mill with CCS (Publication IV)
6. Biomass co-firing (Publication VI)
7. Post-combustion CCS with coal firing in a combined heat and power (CHP) system (Publication VI)
8. Post-combustion CCS with biomass and coal co-firing in a CHP system (Publication VI)
9. Power-to-fuels (PtF) integrated with a CHP system (Publication V)

The analysis is complemented for example with N_2O emissions from Publication I when necessary. In addition, the benefit of CHP over the separated production of power and heat is evaluated based on the results of Publications II and VI. The above-mentioned concepts are presented in more detail in Section 3.7 and in the Publications.

2. Background

Significant deleterious effects of climate change on ecosystems and on human health and welfare were internationally declared already in the Rio Convention in 1992 (UN, 1992). The objective of the Convention was "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*" (ibid.). In total, 197 countries have ratified the Convention (UNFCCC, 2017). Despite this, the concentration of GHGs in the atmosphere has continuously increased (EEA, 2018). Now, over 25 years after the Convention, the concentration of GHGs is still increasing (**Figure 1**). It is evident that more ambitious and effective international policy and local actions are urgently needed.

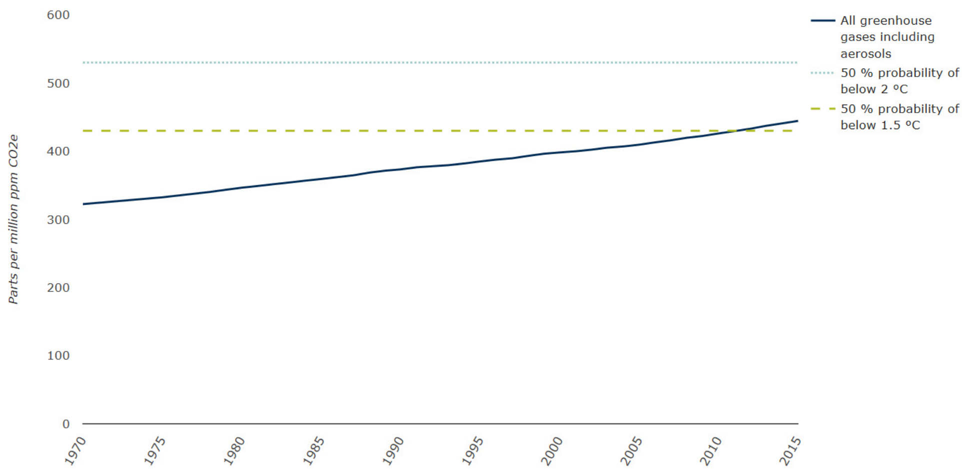

Figure 1. Observed trends in total global GHG concentrations (EEA, 2018). Figure reprinted with permission from European Environment Agency.

Increasing GHG concentrations alter the energy balance of the climate system (IPCC, 2007a). The increase of GHG concentrations is a result of human activities, mainly combustion of fossil fuels (ibid.). Altered energy balance has numerous consequences. It is easy to understand that increased energy in the system increases both global average temperature and atmospheric moisture (ibid.). The further consequences are difficult to predict in detail. Nature has various positive and negative rebounds, impacts have long timeframes and some consequences are irreversible. Impacts are also very different in different geographical locations. Numerous serious impacts of climate change have been presented, for example extreme weather conditions (storms, hurricanes, floods, droughts etc.), changes in local flora and fauna and sea level rise, which can make even entire countries uninhabitable (IPCC, 2007a; IPCC 2007b). Logical consequences of these changes are increasing famine, streams of refugees and potential conflicts (Reuveny, 2007). Even if the magnitudes and frequencies of these consequences are unknown, the implications should be minimised. The later the GHG concentrations are decreased, the more serious will be the consequences, which will mainly influence the next generations who cannot defend themselves against the decisions and actions of our generation.

Globally, the costs related to climate change mitigation and adaptation will be huge (Stern, 2006). Because status quo is not an option, the overall costs should not be compared to zero but rather to other options which are available. Ignoring climate change will eventually damage economic growth. The benefits of strong, early action considerably outweigh these costs (ibid.). It is essential that actions are cost-efficient and lead to truly additional reductions of emissions.

Due to the global nature of the problem and the required actions, international agreements for climate change mitigation have been negotiated under the United Nations Framework Convention on Climate Change (UNFCCC) since 1992. Over the years, it has been difficult to achieve sufficient global actions in the negotiations. Fundamental disagreements are related to differentiated responsibilities of the countries and different national circumstances. The antithetic views have been divided mainly between developing and developed countries, but over the years several kinds of country groups have emerged in the negotiations (UNFCCC, 2018). Different historic emissions, economic capabilities and possible consequences make it difficult to agree globally on the contribution of each country to the costs of mitigation and adaptation. Agreeing on contributions is also known as *effort sharing*, which connects to ambiguous concepts such as fairness and justice.

During the past decade, China has become the world's greatest CO_2 emitter, exceeding the United States (WRI, 2014; Climatechangenews, 2017). In China, GHG emissions per capita are still lower than for example in the United States and in Canada (WRI, 2014). However, climate change is a result of cumulative GHG emissions over many years, which highlights the responsibility of the EU and United States to take more ambitious mitigation actions (**Figure 2**).

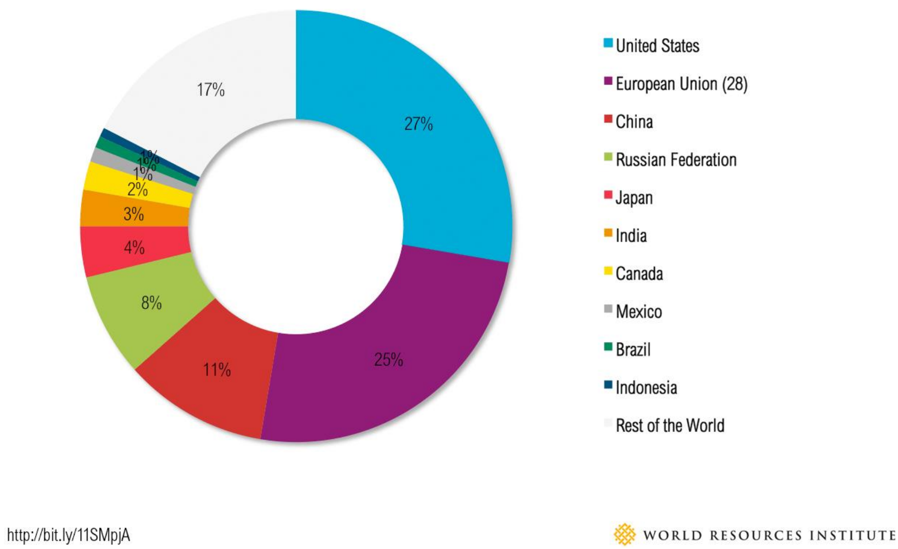

Figure 2. Distribution of cumulative CO_2 emissions between countries 1850-2011 (WRI, 2014). Figure reprinted with permission from World Resources Institute.

The Paris Agreement (UN, 2015) aims to "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*". The Agreement also includes a principle that "*Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition*" (ibid.). The Agreement does not force operators such as companies or investors to specific actions, but sets the long-term framework for countries, which use national policies to meet their targets.

In the EU, Member States have agreed to fulfil their commitments to reduce GHG emissions jointly (EC, 2002) and EU ETS has been chosen as the 'cornerstone' to achieve the reductions (EC, 2017). The term cornerstone, as used by the European Commission, is justified because around 45 % of the European GHG emissions are controlled by this single mechanism. EU ETS is the world's first and biggest carbon market (ibid.).

The EU ETS is described by the European Commission as follows: "*The EU ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by installations covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, companies receive or buy emission allowances which they can trade with one another as needed. They can also buy limited amounts of international credits from emission-saving projects around the world. The limit on the total number of allowances available ensures that they have a value. After each year a company must surrender enough allowances to cover all its emissions, otherwise heavy fines are imposed. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another company that is short of allowances.*" (ibid.).

The EU ETS brings flexibility that ensures emissions are cut where it costs least to do so (ibid.). The approach is reasonable because from the climate change point of view each ton of CO_2 avoided is equally important, but the costs of actions to reduce emissions are not equal. Therefore large emitters ("operators") included in the EU ETS can build into their business whether it is more feasible to decrease the emissions or to purchase and return valuable emission allowances (EUA). The system is also extremely secure to meet the emission reduction target, because there are simply no more emission allowances than the set target.

Basically, all large CO_2 emission sources (e.g. power plants, oil refineries and mills) in the EU are included in the EU ETS (EC, 2017). The emissions excluded from the EU ETS are often called non-ETS sector. The non-ETS sector includes for example agriculture, transportation, waste management and small heating devices, such as oil and gas fired boilers in household scale. Emissions of the non-ETS sector can be effectively maintained by national policies. The ETS sector is strongly regulated by the EU.

The most important contributors to global GHG emissions are power and heat production, transportation, land use change, the cement industry and the iron & steel industry (IPCC, 2014; Ecofys, 2017; CSI, 2017). The distribution of global GHG emissions in different economic sectors is illustrated in **Figure 3**.

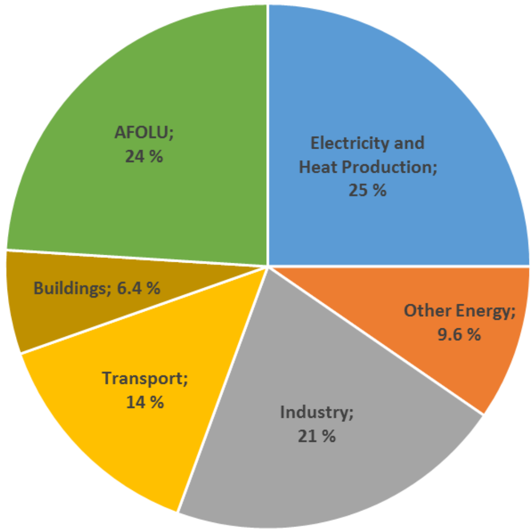

Figure 3. Greenhouse Gas Emissions by Economic Sectors in 2010, when total global GHG emissions were 49 Gt CO_2 eq. AFOLU stands for Agriculture, Forestry and Other Land Use. Attributing GHG emissions from electricity and heat production to final energy use would increase the shares of the sectors “Industry” and “Buildings” up to 32% and 18%, respectively. Values from IPCC (2014).

There are numerous technological solutions to decrease the emissions presented in **Figure 3**. Electricity production by photovoltaic (PV) systems and wind is increasing rapidly (IEA, 2017a). Heat production by solar collectors is becoming more common in both small and large-scale applications (Weiss et al., 2017). Electric vehicles are increasing in road transportation, and the electric car stock may range between 40 million and 70 million by 2025 (IEA, 2017b). Solely these developments may significantly decrease the emissions, because the sectors of electricity and heat production and transport cover almost 40% of global GHG emissions (**Figure 3**).

Despite the developments in solar and wind power, the demand for adjustable and efficient low-carbon and even “carbon negative” electricity and heat production remains and may even increase in the near future, especially in areas with lower annual availability of solar energy. Carbon negative refers to concepts which lead to net removal of CO_2 from the atmosphere on a life-cycle basis. The later the global emissions are decreased, the more carbon negative solutions will be needed, which might become expensive and difficult in practice to realise widely. In this dissertation, CCS combined with bioenergy is an example of the carbon negative concept.

Increasing the share of solar energy also creates markets for seasonal storage of energy (Lewis, 2007; Lehner et al., 2014). In addition, as PV, wind power, solar heat and electric vehicles decrease the GHG emissions of electricity and heat production and transportation, the role of industrial emissions is highlighted. Adequate for these foreseen scenarios for the near future, this dissertation focuses on the concepts decreasing GHG emissions by adjustable renewable power and heat, efficient waste-to-energy utilisation, renewable transportation fuels, seasonal energy storages and solutions for the steel industry.

3. Material and methods

3.1 Overview

The concepts presented in Section 1.1 are evaluated with different system boundaries and from the perspectives of GHG emissions and economic feasibility of CO_2 emission reductions. The considered system boundaries include *direct GHG emissions* and their impacts on *life cycle and system level GHG emissions*.

Direct GHG emissions mean the most significant physical GHG emissions from the flue gas stacks of the considered *point sources*. Large emitters are called point sources, even if the emissions are released from numerous flue gas stacks around a large site, for example a steel mill area, the size of which can be several km^2. Direct CO_2 emissions from a point source, or several point sources owned by the same operator, are in focus when assessing the economic feasibility of the emission reduction actions in the EU ETS. In addition, in the case of combustion processes, direct CO_2 emissions from combustion often dominate the overall GHG emissions of the assessed life cycles.

CO_2 emissions from biomass combustion are accounted carbon neutral in the EU ETS (EC, 2012) and are thus also accounted carbon neutral for the operator in this dissertation. The evaluation of direct CO_2 emissions is based on state-of-the-art methodologies as described in Section 3.2. In a few cases, direct N_2O emissions are significant and are estimated based on the results of Publication I.

Life cycle and system level GHG emissions are complex to estimate and two state-of-the-art methodologies exist as described in Section 3.3. Independently of the used methodology, life cycle and system level studies include ambiguous choices and consequently high uncertainties related to for example spatial and temporal system boundaries (Soimakallio, 2012). In this dissertation, the importance of system level impacts and selected system boundaries is highlighted. In addition, the impacts under the fixed cap of CO_2 emission allowances in the EU ETS are emphasised. These impacts have often been neglected in the assessments.

Furthermore, the impacts of fuels made from captured CO_2 and hydrogen made by electrolysis (aka PtF and *electrofuels)* are evaluated from the system perspective. Because PtF is a relatively new concept considered for a significant role in climate change mitigation, practices to evaluate impacts on GHG emissions vary and the regulation is still immature.

An overview of the studied impacts and system boundaries is presented in **Figure 4**.

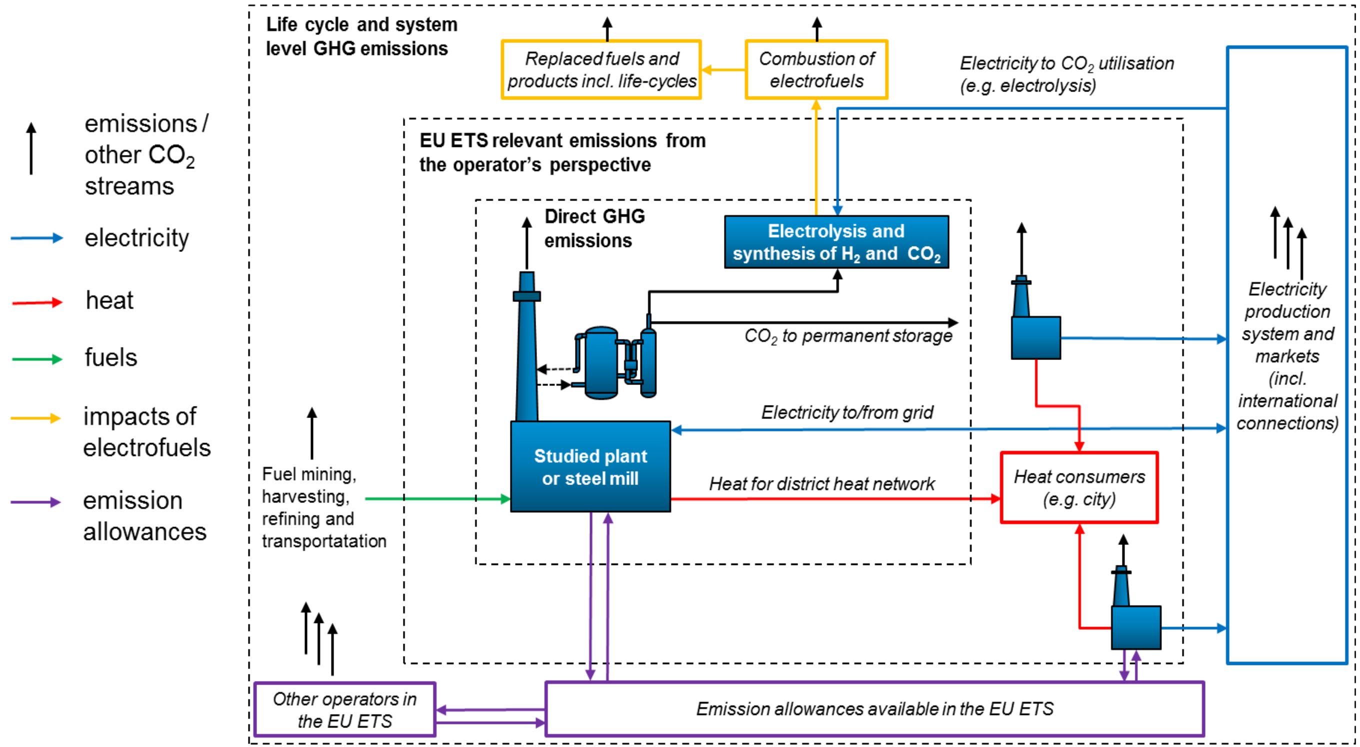

Figure 4. Simplified overview of the studied impacts and system boundaries. Not all of the presented arrows are relevant for every studied concept. EU ETS relevant emissions are crucial in terms of economic feasibility of the concepts from the operator's point of view.

3.2 Direct GHG emissions

There are several possible methods to evaluate direct GHG emissions. The state-of-the-art procedure is to calculate CO_2 emissions from the fuel usage and to use flue gas measurements for the other GHGs. CO_2 emissions are rarely measured in the EU ETS, because the combined accuracy of CO_2 concentration and volume flow measurements can be poorer than the accuracy of the other methods based on fuel carbon content, especially in the case of well-known homogenous fuels such as coal, oil products and natural gas. In addition, if biomass is co-fired with fossil fuels, a third measurement based on C14 isotope would be needed to distinguish between CO_2 of fossil and biogenic origin if measurement-based monitoring is used (Hämäläinen et al., 2007). This is because biomass combustion is considered CO_2 neutral in the EU ETS (EC, 2012), even though relatively high direct CO_2 emissions result from the combustion.

Carbon neutrality of biomass in combustion complies with the guidelines of IPCC, which advises to report emissions from biomass combustion in the AFOLU (Agriculture, Forestry and Other Land Use) sector (IPCC, 2006). The impacts of bioenergy on GHG emissions on a life cycle basis are briefly considered in the Discussion, but the issue is ambiguous and not the focus of this dissertation. In the case studies included in this dissertation, biomass combustion is calculated as carbon neutral according to the current regulation of the EU ETS.

In the case of non-CO_2 GHGs, the accuracy of calculation-based methods is poorer than in the case of CO_2, and flue gas measurements are often needed (Publication I). However, emissions monitored in the EU ETS are limited to CO_2 for most of the plants and therefore calculation-based methods are typically used in the EU ETS. The most common calculation principle is to use data on a plant's fuel usage ("activity data"), carbon content of the fuel ("emission factor") and an oxidation factor. The detailed requirements are presented in the monitoring and reporting regulation, aka MRR (EC, 2012).

Fuel usage is typically well known, and for example the book-keeping data of fuel trade can be used. If activity data is monitored based on net calorific value (lower heating value, LHV), an emission factor (EF) is defined for each fuel as CO_2 emission per LHV of the fuel. Therefore, EF depends on for example the carbon content of the fuel and fuel moisture, and sample-based analyses are often used. The oxidation factor is typically 0.99 or one, meaning that practically all the carbon in fuel is oxidised to CO_2 in large combustion plants (EC, 2012; Statistics Finland, 2017). External accredited verifiers, which are accepted by the national authorities, are used to improve reliability of monitoring and reporting. In the EU ETS, high accuracy of emission monitoring is generally required. The acceptable uncertainty depends on the significance of each source of CO_2, being typically between 1.5 % and 5% for large sources (EC, 2012).

When the plant specific accuracy of the EU ETS is not required, general emission factors for fuels can be used. Reference EFs are also published in the annexes of MRR but in this dissertation, EFs published by Statistics Finland (2017) for the numerous types of fuels combusted in Finland are typically used. Even if the accuracy of general EFs is not always sufficient to be used in the EU ETS, values are well justified for the conducted feasibility and system studies, because the uncertainties resulting due to EFs are minor in comparison to those resulting from other methodological choices and parameters.

For some fuels, emission factors and consequently CO_2 emissions are not well known. For example, fuels based on municipal solid waste (MSW) are so heterogeneous that reliable EFs cannot be given. EFs used for MSW-based fuels are typically based on the analysis of samples, but the representativeness of the sample is uncertain. MSW incineration is typically excluded from EU ETS but co-firing of waste-derived fuels, such as Solid Residue Fuel (SRF) is included. In addition to varying LHV and carbon content of fuels based on MSW, the shares of biogenic and fossil carbon also vary. The EFs used in this dissertation (Publication II) include only the CO_2 from the fossil fraction of waste.

Other means to evaluate direct CO_2 emissions from point sources can be based on the energy balance of the studied combustion plant, mass balance between inputs and outputs or combinations of the presented methods. For example, correlations between continuously measured process conditions and emissions can be used (Publication I).

For Carbon Capture and Utilisation (CCU) and CCS, regulation regarding "*inherent* CO_2" and "*transferred* CO_2" in the EU ETS is important. For example, in a blast furnace based steel mill process, fuels form coke oven gases, blast furnace gases and converter gases. A fraction of these gases, as well as other by-products of the steel mill, may be sold to other operators. In the EU ETS, the carbon included in fuels sold is called Inherent CO_2. Inherent CO_2 can be subtracted from the emissions of the original source if the fuels are sold to other installations regulated by EU ETS. If carbon is transferred to operations not covered by the EU ETS, the subtraction is not permitted, i.e. the carbon is accounted for an emission of the original CO_2 source (EC, 2012).

If carbon is transferred as CO_2, article 49 of MRR, entitled "Transferred CO_2", is applied. So far, only CO_2 transferred to geological storage is permitted to be subtracted in the EU ETS. Furthermore, the MRR limits potential subtraction solely to CO_2 from fossil carbon (ibid.). It is unclear how this limitation would be applied in practice, because in the case of co-firing there are several possible options to allocate biogenic and fossil CO_2 between the captured and vented CO_2. In this dissertation it is assumed that all captured and stored CO_2 can be subtracted from the emissions, because from the climate change perspective the benefit of CCS is independent of the origin of CO_2. Because CO_2 emissions from biomass combustion are zero in the EU ETS, and all captured and stored CO_2 is assumed to be subtracted, the combination of bioenergy and CCS (bio-CCS) creates "negative CO_2 emissions" from the operator's perspective.

Direct CO_2 emissions are also decreased in the case of CCU, although the CO_2 is often released later downstream. If CCU is applied to produce fuels for the sectors not covered by the EU ETS (e.g. transportation), the utilised carbon cannot be subtracted from the emissions of the original source in the EU ETS (ibid.). However, the fuels or products produced from the CO_2 most probably replace other fuels or products, thus creating significant potential for savings in GHG emissions as well. Technically, all the hydrocarbons used in the transportation sector could be replaced by fuels produced from captured carbon and hydrogen produced by renewable electricity. The limitations are in the costs and sufficient regulative framework.

3.3 Life cycle and system level GHG emissions

In life cycle assessments (LCA), emissions from different stages of the life cycle of a product or process and related systems are taken into account. In the literature, two main categories of LCA have been defined: attributional and consequential (Finnveden et al., 2009; Curran et al., 2005). Attributional LCA has been defined as a method "to describe the environmentally relevant physical flows of a past, current, or potential future product system". In attributional LCA, average data is typically used (Soimakallio, 2012). By contrast, consequential LCA aims to describe how environmentally relevant physical flows have been or would be changed in response to considered options (ibid.). Therefore, in consequential LCA marginal data is used when relevant for assessing the consequences (Ekvall & Weidema, 2004). In this dissertation, mainly the principles of consequential assessment are followed when LCA is applied. Typically, the focus in the Publications was on the most important foreseen consequences. This kind of approach can also be called streamlined LCA.

In the case of multiple products or operations in the considered system, there are several possible options for how to allocate emissions between the products. An example of this kind of system is CHP, in which allocation of emissions for heat and power are sometimes applied. For example, energy-based or economy-based allocation logic can be used. However, according to ISO standards, allocation should be avoided whenever possible (ISO, 2006). In the case studies presented in this dissertation, allocation is avoided by expanding the product system also to include the consequences of impacted co-products.

In this dissertation, the focus is on electricity and district heating systems (Publications II, V and VI). The heating systems are local and the assessments can often be made taking into account the properties of all the impacted CHP plants and heat only boilers (HOBs) connected to the system. The consequences of electricity production and consumption are typically reasonable to evaluate taking into account the connections to the broader grid and markets.

As the consequential approach is applied in this dissertation, the concept of marginal electricity is used. Marginal electricity means the type of electricity production in the system which is changing because of electricity production/consumption in the studied case. Because operation costs of low carbon options such as nuclear, solar, wind and run-of-river hydropower (hydropower without significant storage capacity) are low, these production types of electricity are typically operated as a base load in the systems. Energy storages, such as hydropower with storage capacity, can be used to adjust the production, but storages are not considered as marginal electricity in this context, because ultimately the studied changes have no impact on the net electricity production of these options over a longer time span. Marginal electricity is more expensive than baseload and can be a mixture of an adjustable condensing power production portfolio in the system. Therefore, marginal electricity is typically more carbon intensive than average electricity in the systems. The concept is ambiguous and further discussed in Section 5.3.

Direct CO_2 emissions from biomass combustion are accounted as zero, according to the regulations of EU ETS (EC, 2012) and IPCC guidelines (IPCC, 2006). The more detailed impacts of biomass supply on the dynamics of forest carbon balances are not taken into account, but are briefly considered in the Discussion. Similarly, the emissions from the supply chains of other fuels, as well as transportation of captured CO_2 in the case of CCS, are excluded from the emissions presented in **Figure 5** and **Figure 6** of this compilation but are briefly discussed in conjunction with the results and in more detail in Publications II and III.

As described in Section 3.2, CO_2 captured in the EU ETS for utilisation in the non-ETS sector (e.g. for transportation fuels) cannot be subtracted from the emissions of original CO_2 source in the EU ETS (EC, 2012). To avoid double-counting of emissions, the fuel produced from captured CO_2 is assumed to be carbon neutral. Consequently, this principle leads to improved economic feasibility of CCU, because the prices of carbon neutral transportation fuels are significantly higher than those of fossil fuels.

The rebound impacts of considered actions on emission allowances available for other operators in the EU ETS, and consequently on CO_2 emissions are not included in quantitative system analysis because the focus is typically on economic feasibility of operations rather than on broader level emission reductions. However, this rebound effect is very important from the system and policy perspective.

3.4 Economic feasibility

In the studies included in this dissertation, the economic feasibility was typically assessed from the operator's point of view. This means that only the costs and benefits for the operator of the studied plant were taken into account. Similarly, the impacts on GHG emissions were also limited to direct emissions from the considered plant or plants owned by the operator (e.g. connected to the same district heating network, as presented within the EU ETS relevant dashed boundary in **Figure 4**). This means that for example the impacts on the CO_2 emissions from the electricity system are excluded from the analysis of economic feasibility.

Most of the results are presented using break-even price as a key indicator. The break-even price can be defined as the minimum average price of the CO_2 emission allowance in the EU ETS, which should be realised within the considered timeframe in order to make the investment in the studied emission reduction concept economically feasible over the reference case.

The general principle to calculate the break-even prices is presented by Equation (1).

$$Breakeven\ price = \frac{Profit_{reference\ case} - Profit_{studied\ case}}{Emissions_{reference\ case} - Emissions_{studied\ case}} \qquad (1)$$

Where

Profit stands for the net profit of the considered operation (incomes - costs), excluding the costs of CO_2 emission allowances.

Emissions stands for the EU ETS relevant CO_2 emissions in each case

When calculating the profits for Equation (1), typically fuel costs, impacts on other variable operational expenditures (OPEX), impacts on fixed OPEX and capital expenditures (CAPEX) are taken into account. CAPEX is calculated based on the required investment, considered timeframe for the investment and the weighted average cost of capital (WACC). When the investment is estimated based on the investments given for different size units, a so-called scale factor and equation (2) presented in Perry's Chemical Engineers' Handbook (Green and Perry, 2008) are used to approximate the impact of economy of scale.

$$Investment = \left(\frac{Studied\ scale}{Scale_{Given}}\right)^{scale\ factor} \times Investment_{Given} \qquad (2)$$

Where

Studied scale and *Scale*$_{Given}$ mean the parameter on which the investment is considered to be the most dependent, for example, the production capacity of the plant or the flue gas flow.

Incomes (revenues) are taken into account when impacted by the studied concept. This is typical for by-products such as oxygen from electrolysis or electricity from the CHP system. The amounts of main products are typically assumed to be unchanged in the studies of this dissertation, and therefore incomes from the main products are irrelevant from the break-even price point of view. For example, heat consumption in the district heat network is typically not dependent on the studied concepts; only the usage of the heat production portfolio feeding the network varies. Usage of different types of plants may have a significant impact on the electricity produced by the CHP plants of the system, affecting the incomes for the operator (Publication VI). Similarly, the steel production of the studied steel mill was assumed to be independent of the studied concepts (Publications III and IV).

The regulation of the EU ETS was followed in the assessments, but one important exception was made. In feasibility studies, negative emissions were assumed to be additional income for the operators, with the same price per ton of CO_2 as the price of the emission allowance in EU ETS. The rationale for negative emissions is clarified in Section 3.2. If negative emissions are not credited, feasibility studies of bio-CCS are worthless because the case cannot be economically feasible in practice.

The break-even price is sensitive to the prices of fuels, electricity and other parameters, which are very uncertain in the considered timeframes of the studies. Therefore, the results are typically presented as charts including the most important variables, rather than by single values. In addition, special attention has been paid to sensitivity analysis. However, due to the complexity of the studies and numerous variables included, sensitivity analysis for all factors is not possible. Different methods to analyse the sensitivity and uncertainty were used (Publications I-VI).

It is also important to take into account possible inflation if prices and investment costs from several sources dealing with different years are combined. However, the inflation in the Euro area has been very low since 2009, even near to zero in recent years (Eurostat, 2018). The impact of small inflation is negligible in comparison to overall uncertainties related to cost parameters. Therefore, the inflation correction is not applied in the Publications of this dissertation.

In the case of CCU for transportation fuels, subtraction of CO_2 emissions is not permitted in the EU ETS, as explained in Section 3.2. Consequently, the fuel produced from this CO_2 should be considered carbon neutral. Therefore, from the operator's point of view, the captured and utilised CO_2 is not an avoided emission in the EU ETS, but a new by-product (sold CO_2 or further refined product). The income from a carbon neutral product can be estimated to be significant. In the case of CO_2 capture for utilisation, the presented break-even prices indicate the income from CO_2 necessary to make CO_2 capture economically feasible for the operator (Publication VI). The economic feasibility of Power-to-Gas (PtG) was estimated with a fixed purchase price of CO_2, because the price of CO_2 is only a minor share of the overall costs of PtG (Publication V).

3.5 Reference cases

In order to evaluate emission reductions and break-even prices of the studied concepts, reference cases and the respective emissions and costs need to be defined. In this dissertation, the reference cases can be categorised as state-of-the-art of the mainstream solutions for the studied applications (Publication II), scenarios agreed with the associated plant operators (Publications III and IV), or business-as-usual (BAU) scenarios (Publication V). In Publication VI, a clear reference case is not defined, but the studied cases are compared with each other. As the direct GHG emissions are the highest in the case of coal combustion, it can be considered as a reference case. In Section 4.2.1, CHP cases are also compared with separated production of heat and electricity, which can be considered as a reference case for CHP as a general emission reduction concept.

The most important properties of the state-of-the-art technologies are estimated based on the public information. In some cases, sensitivity analysis has been made for the replaced fuels. The reference scenario for the steel mill is based on the existing mill, but a few improvements to the mill are also assumed in the reference case (Publication III). These improvements were considered probable in the near future by the mill operators, and some of them have already been realised after the studies. However, not all improvements in the real mill were foreseen in Publication III. Therefore, the reference case in the OBF study (Publication IV) was slightly different compared to the post-combustion CCS study (Publication III) for the same steel mill. For the studied integration of PtG with CHP, comparison to BAU is based on the existing plant, the surrounding energy system and replacement of fossil gas by the produced synthetic natural gas (SNG).

In order to illustrate the studied concepts in parallel in the Figures of this compilation, the following additional assumptions were made for the reference cases: The considered amount of waste in WtE studies was assumed to be combusted in one year (timeframe was not presented in Publication II). Only one reference steel mill emissions (based on Publication III) are presented in **Figure 5** and **Figure 6**. A peak load utilisation rate of 6000 h/a was used for the reference case CHP plant, for which integration of the PtG concept was studied (in Publication V only the changes on the CHP plant were studied, the annual emissions of the CHP plant were not relevant).

3.6 Summary of the studied concepts and perspectives

The concepts were evaluated from three perspectives, direct GHG emissions, life cycle/system level GHG emissions and economic feasibility. A summary of the studied concepts and perspectives is presented in **Table 1**.

Table 1. Summary of the studied concepts and perspectives.

<table>
<tr><th></th><th>Direct GHG emissions</th><th>Life cycle and/or system level GHG emissions</th><th>Economic feasibility</th></tr>
<tr><td>WtE by BFB and chemical additives</td><td>Publication I (N_2O, CH_4)</td><td rowspan="2">Publication II (CO_2, N_2O, CH_4)</td><td rowspan="2">Not analysed</td></tr>
<tr><td>WtE by CFB and co-firing high ash coal</td><td>Publication II (CO_2, N_2O)</td></tr>
<tr><td>Post-combustion CCS in a blast furnace-based steel mill</td><td>Publication III (CO_2)</td><td>Publication III (CO_2, N_2O, CH_4)</td><td>Publication III
Publication IV</td></tr>
<tr><td>OBF in a steel mill</td><td rowspan="2">Publication IV (CO_2)</td><td rowspan="2">Publication IV (CO_2)</td><td rowspan="2">Publication IV</td></tr>
<tr><td>OBF in a steel mill with CCS</td></tr>
<tr><td>Biomass co-firing</td><td rowspan="3">Publication I (N_2O, CH_4)
Publication VI (CO_2)</td><td rowspan="3">Publication VI (CO_2) *</td><td rowspan="3">Publication VI</td></tr>
<tr><td>CCS with coal firing in a CHP system</td></tr>
<tr><td>CCS with biomass and coal co-firing in a CHP system</td></tr>
<tr><td>PtF integrated with a CHP system</td><td>Publication V (CO_2)</td><td>Publication V (CO_2) *</td><td>Publication V</td></tr>
</table>

* The impacts of altered consumption and production of electricity on system level CO_2 emissions are estimated based on the concept of marginal electricity as described in Section 3.3. For the concepts for which the changes in electricity production were evaluated in the Publications but the system level emissions were not presented, an emission factor of 850 kg CO_2/MWh was used in this compilation (Publication IV).

3.7 Summary of the Publications used

3.7.1 CH_4 and N_2O emissions from fluidised bed boilers (Publication I)

Fluidised bed combustion has many favourable properties for combustion of different types of fuels and fuels of varying quality, e.g. moist biomass residues. One drawback especially in the case of CFB technology are N_2O emissions, which can be significant in some cases. CH_4 and N_2O emissions depend strongly on combustion conditions, which vary between different plants and in time, depending on for example boiler load and fuels. Therefore, the emission factors used in the calculation of annual emissions contain significant uncertainties. The aim of Publication I was to develop and apply an advanced, measurement-based method for the estimation of annual CH_4 and N_2O emissions taking into account the varying conditions around the year.

The study is based on the continuous long-term (up to 50 days) field measurements conducted in seven full-scale industrial and municipal CHP plants utilising fluidised bed boilers. The results represent different size classes, technologies, loadings and fuel mixes. Combusted fuels included coal, peat, biofuels and SRF. Measurement results from different loading levels were combined with the common loading curves of similar plants in Finland in order to estimate annual emissions for national GHG inventories.

3.7.2 Advanced Waste-to-Energy concepts (Publication II)

In Publication II, two advanced WtE concepts were compared with state-of-the-art WtE. Advanced concepts are based on BFB and CFB combustion of waste. In the case of BFB based concept, chemical additives are injected to process enabling higher steam temperatures than currently used in WtE. In the case of CFB concept, waste is co-fired with high ash coal, creating suitable ash chemistry in the furnace.

The both of the advanced concepts increase the WtE efficiency in power production, or power-to-heat ratio in the case of CHP. In condensing type electricity production, efficiencies up to 35% and 41% (based on LHV) are reached by BFB and CFB concepts, respectively. For the reference grate-fired concept, state-of-the-art efficiency of 25% was applied. In addition to electricity production solely, CHP applications were also studied. In CHP applications, the differences in overall efficiencies (heat+power outputs / fuel input) are diminished if all the heat can be utilised. However, local heat consumption is often limiting the utilisation of heat.

A simple energy system model was applied in calculating the GHG emissions in different scenarios in which coal or natural gas was substituted in power generation. A mix of fuel oil and natural gas was assumed to be replaced by the heat produced in CHP cases. In addition to direct CO_2 emissions from combustion, N_2O emissions from CFB concept were also taken into account, as well as GHG emissions from the production and supply of both used and replaced fossil fuels.

3.7.3 CCS at a blast furnace-based steel mill (Publication III)

Publication III is Part II of the study published as coupled articles. In Part II, the economics of the technical possibilities presented in Part I (Arasto et al., 2013) for applying post-combustion CO_2 capture at an integrated blast furnace-based steel mill were studied. Evaluated technical possibilities included different options to supply heat for regeneration of the solvent used for capturing CO_2 from flue gases. Solvent regeneration is typically the main reason for the energy penalty in post combustion CO_2 capture processes and furthermore the major cost component of the technology. There are several possible heat sources in steel mills, resulting in an interesting case study for post combustion CCS. In addition, some major flue gas streams of blast furnace-based steel mill processes have a higher concentration of CO_2 than typically presented in power plant cases, enabling lower investment and capture costs per ton of CO_2.

Studied heat sources included direct utilisation of the main steam from the steel mill's power plant, heat extraction from the power plant's turbine, heat recovery from suitable processes of the studied steel mill and combinations of these options. The capacity of the CO_2 capture plant was determined based on the heat source considered in each case, resulting in different investments, capture costs, reductions in CO_2 emissions and electricity production of the steel mill's power plant. In addition, different solvents were compared. Sensitivity analysis was conducted with different electricity prices, because there was large variation in electricity production between the cases and electricity price is very uncertain over the timeframe of the investment. Captured CO_2 was assumed to be shipped to the North Sea for permanent geological storage, resulting in a significant contribution to the overall costs.

3.7.4 OBF at an integrated steel mill (Publication IV)

Similarly to Publication III, Publication IV is the second part of a study published as two coupled articles. In Publication IV, the economic feasibility of the OBF process was evaluated based on the technical modelling presented in Part I (Arasto et al., 2014). The case study is based on the same existing Finnish blast furnace-based steel mill as Publication III. The feasibility of the OBF process was evaluated both with and without CCS, because the process would significantly decrease CO_2 emissions from the mill even without CCS. The decrease of CO_2 emissions is based on the lower coke consumption of the OBF process in comparison to conventional blast furnaces. However, in the OBF process, a large CO_2 stream is removed from the blast furnace top gas before recycling the remaining gas (mainly hydrogen and carbon monoxide) back to the furnace. Therefore the concept is also known as Top Gas Recycling Blast Furnace (TGRBF). Removed CO_2 is at a high concentration, thus representing an attractive case for CCS. In the case of OBF, pure oxygen is fed into the process instead of oxygen-enriched air in the case of conventional blast furnaces.

From the economic point of view, important consequences of the OBF process are increased consumption of Liquefied Petroleum Gas (LPG) or Liquefied Natural Gas (LNG), decreased electricity production in the steel mill's power plant, increased electricity consumption to produce additional oxygen, required investments and CO_2 transportation and storage costs in the case of CCS. Decreased electricity production is a consequence of the recirculation of blast furnace top gas, which in the reference case is combusted for electricity in the steel mill's power plant. In Publication IV, several sensitivity analyses are presented with different prices for CO_2, electricity and other parameters. The data from Publication III is also included in the results in order to compare these major CO_2 reduction options of the mill.

3.7.5 PtG integrated with biomass fired CHP plant (Publication V)

PtG and more generally PtF are recognised as potential options to benefit from periods of low electricity prices or even surplus electricity in the systems. Temporary low electricity prices will probably be more common in the future due to the increasing shares of solar and wind energy in power systems. PtG can be used as a seasonal energy storage or to produce valuable fuel for transport. Typically, PtG is based on electrolysis to produce hydrogen, which is then used for example in synthesis with CO_2 to produce hydrocarbons. Even if the CO_2 is finally released in the case of combusted hydrocarbons, fossil fuels are often replaced and consequently CO_2 emissions are decreased.

In electrolysis, a significant amount of oxygen is produced as a by-product. There are several possible small-scale usages for purified oxygen, but if PtG becomes feasible to a wide extent, surplus oxygen will be available in relatively high concentration. One option for large-scale utilisation of oxygen is to use it for enrichment of the combustion air of several combustion processes. By-product oxygen is directly suitable for combustion air enrichment and purification is not needed. In the concept studied in Publication V, oxygen is temporarily used in a biomass fired or co-fired CHP plant to increase production during periods of peak prices. This requires oxygen storage, because electrolysis is operated during periods of medium and low electricity prices. In addition to temporal increases of production, oxygen enrichment may also lead to other benefits, such as higher efficiency, improved process control, decreased emissions and new fuel options.

Oxygen enrichment also increases the CO_2 concentration of flue gases, slightly decreasing the costs of CO_2 capture. In Publication V, CO_2 is captured from the small side stream of CHP plant flue gases and utilised in the synthesis with hydrogen from electrolysis. Because in the CHP systems recoverable heat and steam from PtG process can also be utilised, integration of PtG with a biomass-fired CHP plant offers an attractive concept for future energy systems. In Publication V, the feasibility of this concept is analysed in several market scenarios.

3.7.6 Bioenergy and CCS/U in a large CHP system (Publication VI)

The debate on energy is often focused on electricity, although heating and cooling are even more important. In Europe, heating and cooling are responsible for almost 50% of the overall energy demand (RHC, 2014). By CHP or combined heating, power and cooling (CHPC), consumption of fuels and consequently several emissions can be significantly decreased in comparison to separate production of the respective amounts of these commodities. In Publication VI, selected options to further decrease CO_2 emissions from one of the most highly developed large CHPC systems in the world were investigated. Case studies were based on a multi-fuel CHP plant, which is one of the possible developments of the CHPC system. For a multi-fuel plant, four cases were investigated including coal firing, co-firing a high proportion (80% of LHV) of forest residues with coal, applying post-combustion CCS or CCU to coal firing, and combination of CCS or CCU and biomass co-firing. CCS and CCU options were dimensioned for 50% flue gas stream, capturing 90% of the CO_2 from that.

The studied cases are different in terms of district heat and power production capacities of the multi-fuel plant. In addition, the operation costs of the multi-fuel plant in different cases varies. These differences impact on the operation of the entire CHPC system. From the operator’s point of view, the profitability of the entire system is more important than the profitability of a single plant. The impacts of the investigated cases on the profitability of the system were compared in different market situations.

4. Results

The impacts of the studied concepts are illustrated in this section from three perspectives, namely direct GHG emissions, energy system level GHG emissions and economic feasibility. The selected cases and scenarios are included in this compilation, and more results and sensitivity analyses are presented in the Publications I-VI.

The results consist mainly of CO_2 emissions from influenced combustion processes. In addition, N_2O emissions are presented for CFB boilers in **Figure 5** and are included in direct GHG emissions in **Figure 6**, even though N_2O emissions from power plants are not accounted for the operator in the EU ETS or in the economic assessments of this Dissertation. N_2O emissions from BFB boilers, and CH_4 emissions from large combustion plants in general, are not significant in comparison to the other studied emissions (Publication I). Therefore, these emissions are not included in **Figure 5** or **Figure 6**.

4.1 Direct GHG emissions

Direct GHG emissions of the studied concepts are illustrated in **Figure 5**. Only the emissions from the studied plant or mill are presented in the figure, excluding for example the impacts on the other plants of the same district heating network, even if the plants were operated by the same operator.

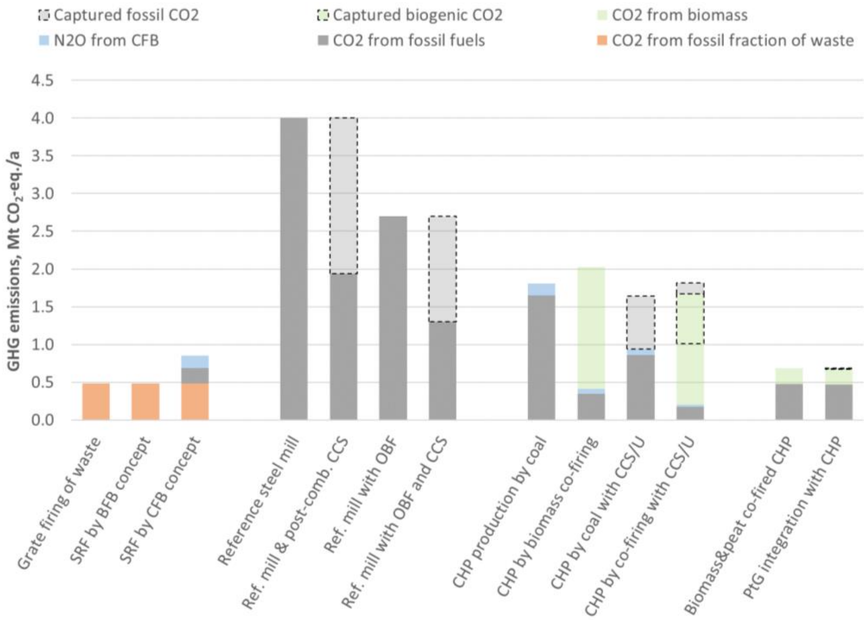

Figure 5. Selected examples of the direct GHG emissions from the studied concepts compiled from Publications I-VI. For waste-based fuels including both the biogenic and fossil fraction, CO_2 emissions only from the fossil fraction are presented. CO_2 emissions from the combustion of biomass and N_2O emissions from CFBs are depicted by transparent green and blue, respectively, because these emissions are not accounted for the operator in the EU ETS. In addition, captured and utilised or permanently stored CO_2 is presented as transparent with dashed lines, because these emissions are not physically emitted from the plants to the atmosphere.

As presented in **Figure 5**, direct GHG emissions from the fossil fraction of waste are equal between the studied WtE concepts. This is because the studied amount of waste was assumed to be entirely combusted in every scenario, resulting in equal CO_2 emissions. For the CFB-based concept, CO_2 emissions from coal co-firing, as well as the N_2O emissions lead to higher direct GHG emissions. N_2O emission is significant in comparison to fossil CO_2 in this case. However, the benefit of this concept will become evident in the following section, where the impacts on the connected energy systems are taken into account.

In Publication III, several cases were presented for different size post-combustion CCS applications in a blast furnace-based steel mill. In **Figure 5**, the selected case based on monoethanolamine (MEA) solvent is presented, including a moderate sized capture plant (case 3 of Publication III) applied for the most important flue gas streams of the mill. The presented case would have a significant impact on the direct GHG emissions of the mill. However, this would require steam bleed from the turbine for the recovery of the used solvent, decreasing the electricity production. Consequently, the net electricity purchase of the mill would increase.

An OBF would decrease most of the direct CO_2 emissions of the steel mill with CCS, but significantly also without CCS due to the decreased coke consumption. The reduction could be even greater, because it was assumed that coke production remains constant and the surplus coke is sold. Decreased coke production would further decrease CO_2 emissions but also impact on the gas balance of the whole steel mill due to decreased coke oven gases, which are currently utilised on-site, for example in the rolling mills. Both the concepts, OBF and OBF with CCS, would remarkably increase the electricity purchase from the grid, which is not visible in **Figure 5**, but is illustrated in Section 4.2.

In **Figure 5**, the illustrated cases from Publication VI present the scenarios in which the considered plant is the first in merit order. Using biomass firing or co-firing in CHP would drastically decrease the GHG emissions, as bio-based CO_2 is accounted carbon neutral. Physical CO_2 flow from the CHP plant is slightly greater in the case of biomass co-firing than in coal combustion. This is mainly because of the lower LHV of moist biomass (higher carbon/LHV ratio of fuel) in comparison to coal. N_2O emissions from coal combustion in CFB are significant, although minor in comparison to fossil CO_2. N_2O emissions decreased with biomass co-firing (with a large share) in comparison to coal firing alone, based on the measurement results presented for biomass firing and co-firing in CFB (Publication I).

Post-combustion CCS for 50% of the flue gas stream decreased direct GHG emissions by almost 50%. CO_2 capture also decreased N_2O emissions, because these emissions are probably removed either before or during the capture process (Pihkola et al. 2016). CO_2 capture significantly affects the production of electricity and heat, which are not visible in **Figure 5** but are highlighted in **Figure 6**. In the case of biomass co-firing with CCS, so-called "negative CO_2 emissions" are achieved, if biomass combustion is accounted carbon neutral. This means that the operator could gain money by biomass combustion and CCS, if the EU ETS would acknowledge the negative emissions. However, regulation of the EU ETS is still illogical from this perspective and only the captured fossil CO_2 can be subtracted from the emissions, as described in Section 3.2.

In **Figure 5**, the "base case" of Publication V is presented with and without PtG integration. With the default values, the amount of oxygen from electrolysis is sufficient to use oxygen-enriched air only during periods of peak prices, whereas the PtG plant is operated almost around the year. Increased fuel use enabled by oxygen enrichment slightly increased the CO_2 emissions of the CHP plant, but also increased the production of electricity and heat during periods of peak demand. By contrast, the heat recovered from electrolysis and synthesis for district heating decreased the combustion in the CHP plant and consequently the electricity production and emissions. In addition, a small share of CO_2 emissions was utilised as synthetic fuel. The electricity consumed annually in electrolysis is more than the additional electricity production with oxygen enrichment. Consequently, the net impacts of the studied case are decreased direct CO_2 emissions, decreased electricity production and increased heat production.

Due to the differences in the scales of typical CHP plants and state-of-the-art PtG processes, the net impacts of the studied PtG integration are small in comparison to the annual CO_2 emissions of the CHP plant, and therefore hardly visible in **Figure 5** and **Figure 6**. Technically, the concept is scalable and duplicable, but a larger PtG plant would increase the utilisation time and/or share of oxygen enrichment in CHP and the amount of recoverable heat, leading to case specific limitations, for example utilisation of heat. In addition, technical changes are required at some point, if the share of oxygen is further increased. For example, expensive materials or flue gas re-circulation may be required, leading also to different consequences in terms of CO_2 emissions, electricity production, etc.

4.2 Life cycle and system level GHG emissions

As presented in Section 4.1, studied CO_2 reduction concepts significantly affect the produced heat and power of the considered cases, as well as the consumptions of fuels. When the analysis is extended also to consider the connected heat and power systems, the results differ from the direct emissions remarkably (**Figure 6**). The replacing power and heat productions are calculated for each case to cover the differences from the highest production of the respective commodities among the cases of the same point source. Therefore, the presented cases of the same point source are more comparable than in **Figure 5**.

CO_2 emissions from the replacing electricity are calculated based on the concept of marginal electricity (Publications II, III and IV). Emissions from replacing/replaced heat production are case specific, depending on the local heat production portfolio. Heat utilisation is also regionally and seasonally limited, contrary to electricity, which is typically connected to a much broader grid. In **Figure 6**, “Other heat production” includes only the differences in replacing/replaced heat production altered by the cases, i.e. the overall GHG emissions from the studied CHP systems (e.g. the other plants feeding the network) are not presented.

In **Figure 6**, condensing power cases of studied WtE concepts were presented in order to highlight the differences between the concepts, and because from the global point of view it is common that not all the heat from WtE plants is utilised. Like WtE plants, steel mills could typically also supply more heat than the local consumption. Therefore, the impacts of changes in heat production are not visible in **Figure 6** for the WtE and steel mill cases.

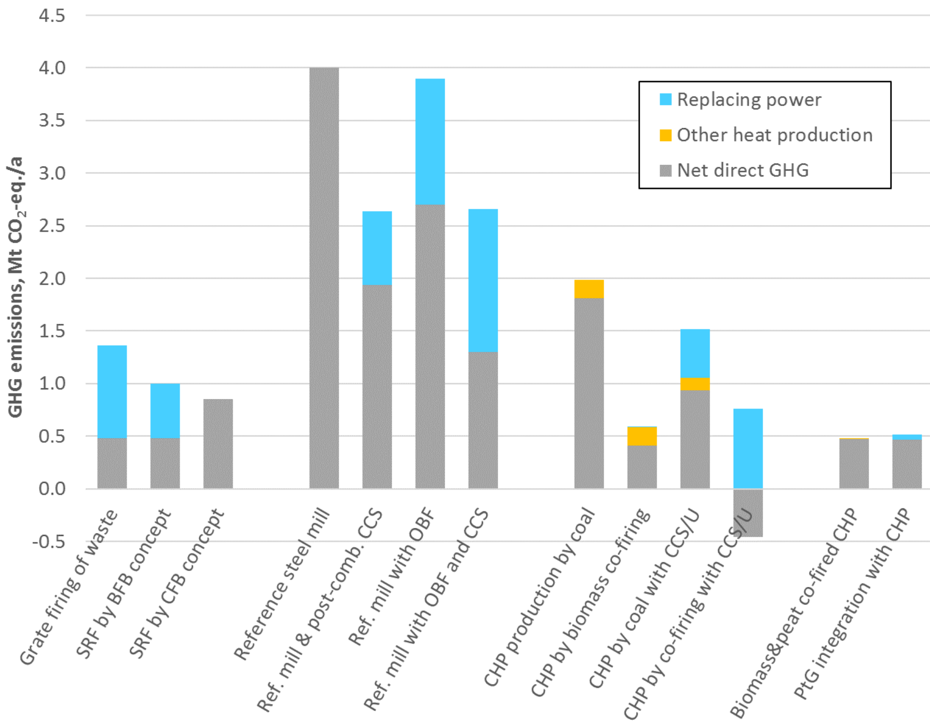

Figure 6. A summary of the GHG emissions of the studied concepts based on system level studies. Net direct GHG includes the emitted fossil CO_2 and N_2O, and excludes emitted biogenic CO_2 and captured fossil CO_2. Consequently, negative emissions are achieved by captured biogenic CO_2. Captured CO_2 is excluded independently of whether it is permanently stored or utilised. The replaced emissions from the products and fuels substituted by CCU are not speculated in this figure. For the replacing power, CO_2 emissions from electricity production by coal were used based on the typical marginal production in current power systems.

From **Figure 6**, the benefits of WtE concepts with high efficiency in power production alone can be seen. According to the results of Publication II, there is a climate benefit from the high power-to-heat ratio of studied WtE concepts in the case of CHP systems as well, if coal-based electricity is replaced by additional power production. However, if all the heat from a WtE plant can be utilised, the differences between the WtE concepts are smaller than in the case of power production alone.

In the case of the studied steel mill concepts, the GHG emissions from replacing electricity production are also highlighted. Especially the concepts based on OBF increase the net purchase of electricity, because the electricity production in the steel mill's power plant is decreased and simultaneously the consumption is increased. The electricity consumption is further increased in the case of

CCS, due to the purification and compression of CO_2. However, significant reductions in CO_2 emissions are achieved in the cases with CCS, even if coal-based electricity is assumed to replace the increased purchase from the grid.

In Publication VI, the co-firing case with CCS/U resulted in the highest heat production. Smaller heat production in other cases results in higher utilisation and emissions of other units in the district heat network compared to the co-firing case with CCS/U. High production of heat in the co-firing case with CCS/U is a result of the flue gas condenser, which is required in CO_2 capture cases. In the co-firing case, moist biomass increases the heat recovery in the flue gas condenser.

In CHP cases, the differences presented in **Figure 6** for GHG emissions from "Other heat production" are small, because on the system level an equal amount of district heat is produced (consumed) in all the cases and the cases are compared with the same merit order of the plants. Impacts on GHG emissions from replacing electricity production are more significant. Especially in the case of co-firing and CCS/U, electricity production is decreased due to the energy penalty of CCS/U in the plant, but also due to decreased utilisation of other CHP plants in the network. Utilisation of the other plants is decreased because of the additional heat recovery from the studied plant.

For the co-firing case with CCS, negative direct emissions are visible in **Figure 6**. Although CCU is presented as an alternative to CCS for these concepts of Publication VI, the impacts do not include the potential electricity consumption of CCU, which would be high if all the captured CO_2 were to be utilised as electrofuels. However, there are also other alternatives for CO_2 utilisation than routes based on electrolysis.

Contrary to Publication VI, utilisation of CO_2 was the focus of Publication V and the electricity consumed in electrolysis, as well as other impacts of CCU, are included in the impacts of this concept in **Figure 6**. Because carbon intensive marginal electricity was used in the assessments, net GHG emissions increased with this concept. The importance and ambiguousness of the impacts on the power system are highlighted and reflected in the Discussion.

4.2.1 The benefit of CHP

CHP is linked to all of the studied concepts. N_2O and CH_4 measurements were conducted in CHP plants (Publication I). Steam and heat are needed in a steel mill, making CHP favourable (Publications III and IV). For other concepts, the benefits of CHP can be compared to separated production of heat and power. For the studied WtE concepts, the system level GHG emissions were 14% - 50% lower in the case of CHP in comparison with power production alone (Publication II).

In **Figure 7**, the benefits of the CHP cases studied in Publication VI are illustrated by comparing the system level GHG emissions with separated production of the corresponding amounts of heat and electricity by HOBs and marginal electricity (850 kg/MWh), respectively. CO_2 emissions from HOBs are estimated on the basis of the mixture of light and heavy fuel oil (Publication VI). The results can also be applied to the comparison with household-scale oil and gas fired boilers, for which the benefit is slightly smaller due to lower emission factors than for the studied mixture of oils.

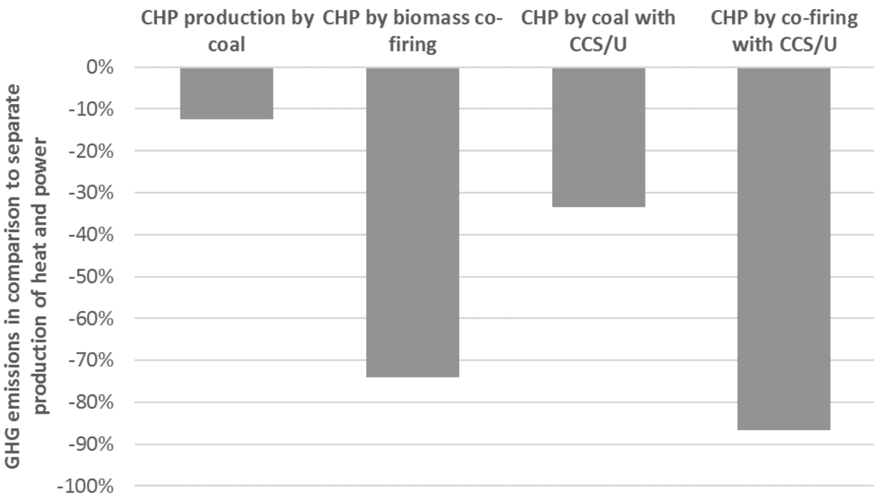

Figure 7. The system level GHG emissions of CHP cases studied in Publication VI in comparison with the impacts of separated production of heat and electricity. For separated production, oil-fired HOBs and marginal electricity (850 kg CO_2/MWh) are assumed.

According to **Figure 7**, the benefit of CHP over separated heat and power production is clear. It is remarkable that even coal-based CHP production would decrease the direct GHG emissions in comparison to separated production of heat and power, because of high overall efficiency of CHP in comparison to separated production and the emission factor of marginal electricity. The benefit of CHP is strongly dependent on the alternative heat sources. In the Discussion, CHP is compared with electricity-based heat sources (electric heaters, boilers and heat pumps) with different system boundaries.

4.2.2 Fuel supply and transportation of CO_2

In addition to the impacts presented in **Figure 6**, some of the studied concepts also have significant consequences for the GHG emissions from the altered fuel supply chains. The GHG emissions from the selected coal mine types are presented in **Table 2**, emphasising the differences between the coal mine types and coal LHV. LHV is strongly dependent on the ash content of the coal, which varies between the coal types and mines.

Table 2. The indicative impact of coal mine type and LHV on CH_4 emissions (Publication II)

Origin	Coal LHV, MJ/kg	Mine type	g CH_4/MJ
Poland / Russia	27.2	Underground	0.29 - 0.76
Poland / Russia	17.7	Underground	0.44 - 1.17
Russia / Australia / South Africa	17.7	Open pit	0.01 - 0.09
Russia / Australia / South Africa	11.3	Open pit	0.02 - 0.14

Long-distance transportation of coal may significantly increase its GHG emissions. For example, a long 13 000 km overseas freight would increase the GHG emissions by about 10 g/MJ (Publication II). Large variations and uncertainties are also related to the emissions of the supply chains of other fuels. Because the supply of fuels typically results in GHG emissions less than 20% of the CO_2 from combustion, and fuel supply chains are also associated in the reference cases decreasing the difference in the emissions from fuel supply chains, the impacts of altered fuel supply chains on the overall GHG impacts of the studied concepts are excluded from the figures of this dissertation.

GHG emissions from transportation of CO_2 are estimated to be minor (Publications III and VI). The GHG emission from transportation was estimated to be about 2% of the captured emissions (Publication III). The emissions result from fuel consumed by the ships, but also from cooling of CO_2 during the voyage. Cooling can be conducted by several different methods, leading to different impacts.

4.3 Economic feasibility

Economic feasibility was analysed in Publications III - VI. In these calculations, only the costs and CO_2 emissions of the studied operators are taken into account. This approach corresponds to the boundaries relevant for the operators in the EU ETS, with one exception. This exception is related to negative emissions and is explained in Section 3.4.

Because the regulation of the EU ETS is followed (with one exception), the calculated break-even prices represent the average prices of CO_2 emissions allowances in the EU ETS, which are required to make the considered concepts feasible over the compared cases. Unlike the emissions presented in previous sections, the break-even prices are also more comparable between the different applications.

The break-even prices are sensitive to the assumed prices of fuels, electricity and heat, WACC and the considered timeframe, as well as to several other parameters included in the studies. In the following figures, sensitivities to the selected factors are presented. However, the assumed default values are used for numerous parameters, resulting in uncertainty of the results due to e.g. fluctuation of prices in the markets and general variation in plant-specific properties.

The break-even prices of the studied concepts for large reductions of CO_2 emissions from blast furnace-based steel production are illustrated in **Figure 8** (Publications III and IV).

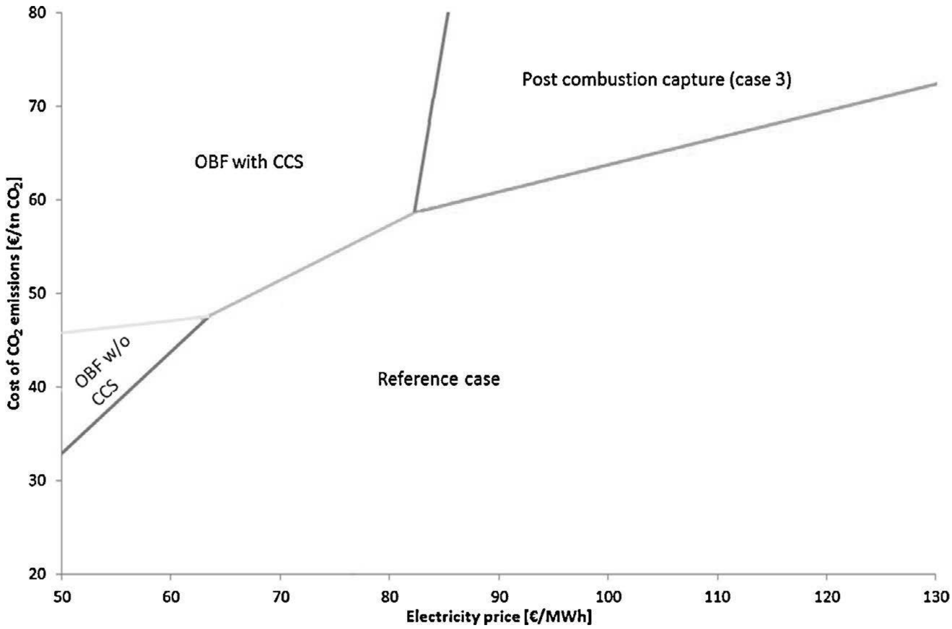

Figure 8. The most profitable concepts among the studied options for a blast furnace-based steel mill in different market conditions. The break-even prices for CO_2 emission allowances between the concepts and the reference case indicate the costs of avoided CO_2 emissions in comparison to the reference case. The lines between two emission reduction concepts should not be considered as break-even prices with the reference case, because these comparisons are made between the concepts. The default cost of LPG (or LNG) is 60 €/MWh, and the selling price for coke is 300 €/t. WACC 10% with a 20-year timeframe was used (Publication IV). Figure reprinted with permission from International Journal of Greenhouse Gas Control.

It can be seen from **Figure 8** that the break-even prices of the studied concepts are strongly dependent on electricity purchase price (including transmission costs and taxes). This is a consequence of the massive increase of electricity purchase in the studied concepts, especially in the case of OBF. With the electricity prices possible in Nordpool markets for the near future (below 30 €/MWh, excl. transmission and taxes), OBF is economically a more feasible option than post-combustion CCS. However, the change to OBF would represent a huge change in the process and would be made during the scheduled renovation of the blast furnaces, of which the lifetimes are about 30 years. Therefore, an easier retrofit and a lower risk to the core process are significant benefits of post-combustion CCS. The costs of CO_2 emission allowances required to make OBF more feasible than the reference case are 30-50 €/t CO_2 with the electricity prices foreseen in near future.

The break-even prices between the different cases studied in Publication VI are presented in **Figure 9**, highlighting the sensitivity to the costs of forest residues. The break-even prices are compared between the studied concepts, i.e. there is no clear reference case in this study. With the present price level for biomass (and coal taxation in Finland), coal firing is more profitable than biomass firing only with very low prices of CO_2 allowances. With the foreseen prices, co-firing of a high proportion of biomass with coal appears to be the most profitable option among those compared. The break-even price between biomass co-firing and 50% CCS is between 30 and 40 €/t CO_2.

Because the CO_2 transportation and storage costs can almost be avoided in the case of CCU, the break-even price to capture CO_2 for utilisation in the studied case is below 20 €/t CO_2 (Publication VI). However, this is not the break-even price for a profitable overall CCU chain, because the costs of utilisation are not included. Therefore, the break-even price in this case represents the price which the operator of the studied CHP plant should obtain from sold CO_2 to make the capture investment feasible. The costs of further purification of CO_2 for utilisation purposes are assumed to be met by the downstream operators.

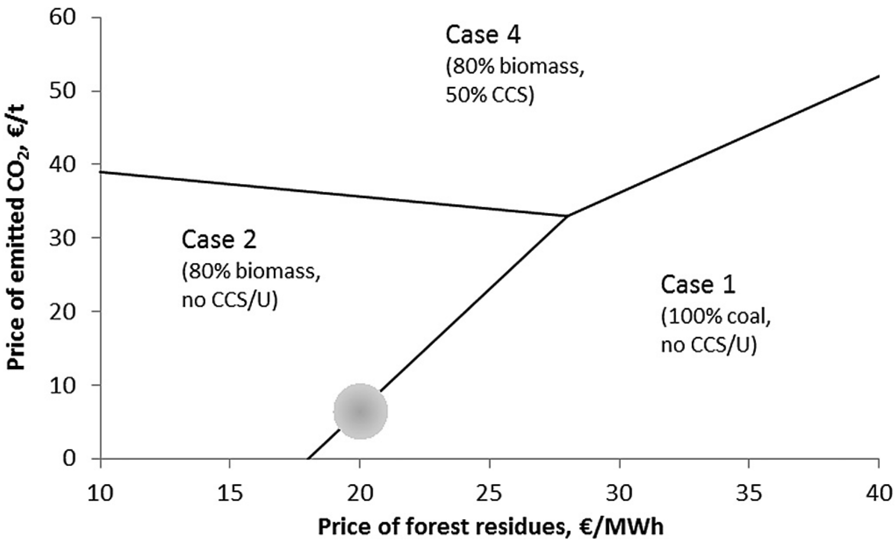

Figure 9. The most feasible studied CHP cases as functions of prices of CO_2 emission allowances in the EU ETS and biomass purchase, using the default values for the other parameters (e.g. electricity sale 60 €/MWh, natural gas purchase 38 €/MWh, WACC 5%, 20-year timeframe). The market situation in 2017 is indicated with a filled circle. In 2018, the price of the CO_2 emission allowance has increased to over 15 €/t (Publication VI). Figure reprinted with permission from Energy.

In **Figure 10**, the respective break-even prices as in **Figure 9** are presented, highlighting the sensitivities to the altered parameters. CO_2 transportation and storage costs are set to zero (simulating break-even price at the plant gate if CO_2 is sold for utilisation) and electricity price is decreased or natural gas price (or tax) is increased. All these changes make the investment and operation of CCU more feasible, leading to very low break-even costs. The assumed electricity price is realistic in the near future, indicating that CO_2 capture for utilisation could be economically feasible in the studied case if a large user of CO_2 exists. However, a significant share of the benefit results from heat recovered from the flue gas condenser, which was not included in the compared cases without CO_2 capture, but could also be invested in these cases.

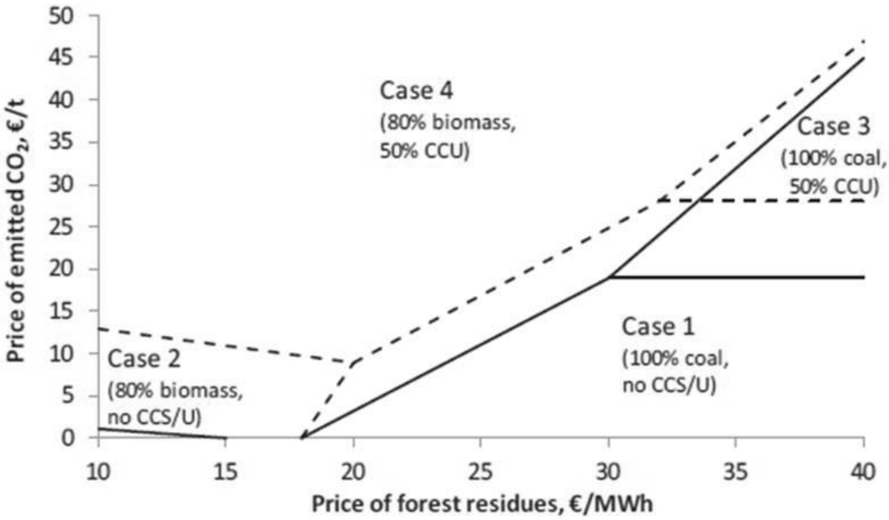

Figure 10. The most feasible studied CHP cases when CO_2 transportation and storage costs are set to zero and the market price of electricity is 40 €/MWh (solid lines). Dashed lines illustrate break-even prices if the cost of natural gas is 45 €/MWh and the default cost of 60 €/MWh is used for electricity (Publication VI). Figure reprinted with permission from Energy.

The economic feasibility of CCU was also studied from the perspective of PtG operator (Publication V). A fixed price of 40 €/t CO_2 was assumed for CO_2 capture and purification (or for CO_2 purchase if bought from other operators). The assumed price is significantly higher than the break-even prices presented in **Figure 10**. The higher price can be justified by the smaller scale of CO_2 capture and the additional purification of CO_2 for utilisation purposes, as well as the above mentioned reason (flue gas condenser) for low capture costs of **Figure 10**. However, the main cost factors in the PtG concept are CAPEX and electricity purchase, and the importance of the price of CO_2 is minor, which can be seen from **Figure 11**.

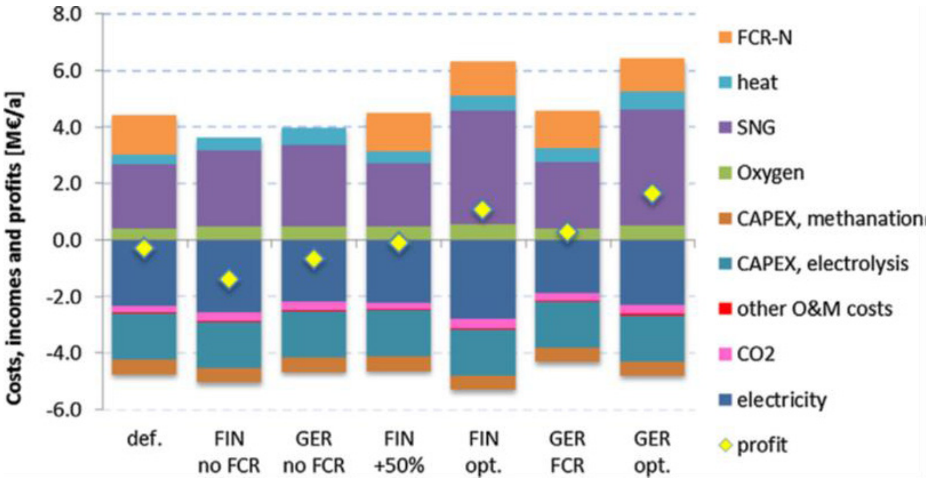

Figure 11. The distribution of costs and incomes in selected scenarios simulated for a PtG concept integrated with a CHP plant. The overall profit of each case is indicated by yellow points. Realised market prices of electricity during 2013 and 2014 in Finland and Germany were used in other simulations, but in the scenario “FIN +50%”, volatility of the electricity market prices was increased by 50%. The default price for produced SNG was 75 €/MWh, but in the optimistic scenarios (FIN opt., GER opt.) a price of 100 €/MWh was used together with higher efficiency of the electrolysis. In all the scenarios, WACC 5% and a 10-year timeframe were used (Publication V). Figure reprinted with permission from Journal of Energy Storage.

From **Figure 11**, it can be seen that the additional incomes from heat and oxygen, enabled by the integration of PtG with the CHP plant, are important in comparison to the overall profit in all the considered cases. However, the income from SNG is clearly the most important income. Potential incomes from the markets for grid frequency containment reserves (FCR) may also be important, but the present size of the FCR-N market in Finland is small. Therefore the results without FCR operation are also presented. Without FCR option, the full load operation increases, increasing production and electricity consumption. However, the net profit decreases.

It appears that the PtG concept integrated with a CHP plant will be feasible in the near future, as several parameters may develop in a propitious direction. With the default values, additional incomes from FCR are required for a business case. Because the share of CAPEX is significant, a longer timeframe than the used 10 years would improve the profitability. Better profitability is also achieved with lower WACC or decreased investment (or investment subsidy). The sensitivity of the payback time to WACC and investment is presented in **Figure 12** for the default case with realised electricity prices in Finland.

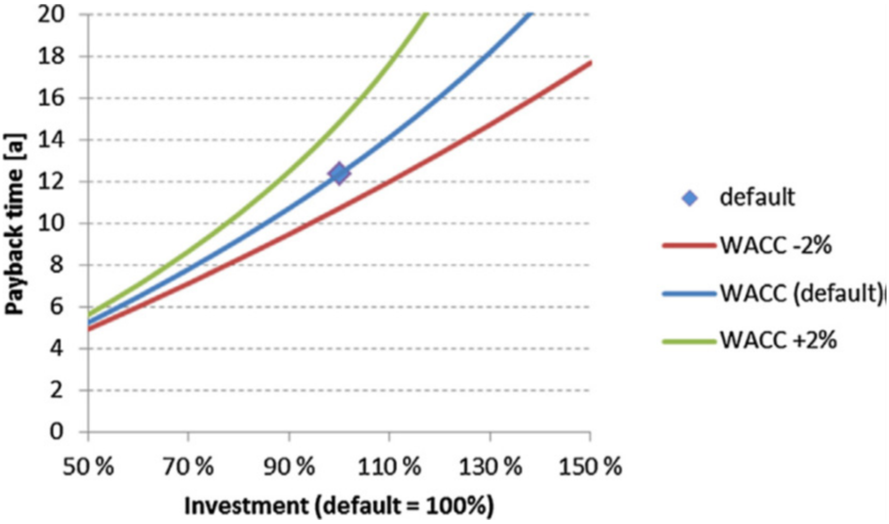

Figure 12. The sensitivity of payback time of the PtG concept integrated with CHP on investment and WACC (Publication V). Figure reprinted with permission from Journal of Energy Storage.

5. Discussion

5.1 The playground

The need to take strong and concrete actions to mitigate climate change is urgent. The actions should be ambitious, effective and truly additional. They should not lead to a rebound, in which emissions are increased elsewhere on the planet. The overall costs to mitigate climate change will be huge, as are the costs of the consequences of climate change. Because each ton of emitted CO_2 is equally harmful independently of its source or the location from which it is emitted, mitigation actions can be conducted starting from the most cost-efficient ones.

The EU has chosen the EU ETS as a cornerstone for EU's climate policy. The EU ETS covers about half of the GHG emissions of the EU. Another half of the GHG emissions is regulated mainly by national policies, but the targets are guided by EU level regulation. A cap and trade system such as the EU ETS has several pros and cons. It should direct the emissions reductions to the most cost efficient actions. In addition, the decided target of emissions will be achieved independently of the economic up and down terms, fuel prices and other varying parameters in the markets, which is not necessarily the case with other policy mechanisms. However, the regulation of the EU ETS makes the impacts of overlapping actions complex, as discussed in Section 5.4.

The importance of the frameworks set by the policymakers and regulators is huge in terms of the effectiveness of the actions of individuals, organisations and companies. Unfortunately, voluntary actions, which would appear favourable at first sight, may actually increase the GHG emissions of the broader system. The crucial importance of the system boundaries is illustrated by the examples in Section 5.5. Contradictory information is confusing for the public and extremely harmful regarding the willingness to participate in voluntary actions.

5.2 Performance of the studied cases and related uncertainties

The case studies presented in this dissertation are different in terms of technologies, applications, scales and approaches. The results are sensitive to several parameters. Consequently, the results also vary and are not directly comparable between the applications. The results are presented in figures as functions of key parameters rather than by single values. However, only a limited number of sensitivities can be included in the results.

There is uncertainty related to all the parameters used in the studies. Furthermore, the results are often even more sensitive to the methodological choices than to individual parameters. Methodological choices are for example the chosen approach (e.g. consequential or attributional analysis) and the selected system boundaries. The lowest uncertainty is related to the determination of direct emissions of the studied plants. The GHG emissions can be measured, calculated from the data of fuel trade and fuel properties, or calculated from process data, or combinations of these. The calculation based on fuel properties is the most commonly used method in the EU ETS and it is relatively precise in the case of homogenous fuels, such as coal and natural gas. In the EU ETS, uncertainties below 2.5 or 5% are typically required depending on e.g. plant size. In the case of heterogeneous fuels, such as waste-based fuels, the emission factors based on fuel properties are more uncertain. Even if the properties are based on analyses of samples of the fuel, representative sampling from the heterogeneous fuel is problematic.

The uncertainty and ambiguousness of the studies increase the broader are the considered systems and the studied life cycles. The presented system level emissions are highly uncertain and are dependent on several assumptions and limitations. Consequently, the costs of avoided direct GHG emissions are more certain than the costs per impact on a system level. Therefore, the impacts on the system level should be considered with care, paying particular attention to the rebound impact from the EU ETS discussed in Section 5.4. There are also other rebound impacts which are less obvious than the impact on available emission allowances. For example, increased electricity production has a marginal decreasing impact on the electricity price, which may have a rebound impact on additional electricity consumption. Decreased coal consumption may decrease coal price and thus increase coal consumption. These rebound impacts are difficult to estimate and are therefore typically excluded from the studies.

A good example of the large difference between direct GHG emissions and system level GHG emissions is a steel mill case, in which an oxygen blast furnace (OBF) was applied to decrease direct CO_2 emissions from the mill (**Figure 5**). However, there was only a small decrease in the emissions on the system level, because of a large increase in steel mill electricity purchase (**Figure 6**). Based on recent news from the steel industry, the potential future pathway is hydrogen-based iron ore reduction (SSAB, 2017). Even if the hydrogen-based reduction process totally differs from the studied OBF concept, a huge increase in electricity purchase takes place in both these concepts.

Contrary to the steel mill concepts, the studied WtE concept with coal co-firing in CFB increased electricity production from the same amount of waste, but the direct GHG emissions also increased due to coal co-firing and N_2O from CFB (**Figure 5**). Consequently, the system level emissions (**Figure 6**) are lowest in the case in which direct emissions are the highest. The system level emissions of most of the concepts studied in this dissertation are very sensitive to the emissions assumed for the consequences to the wider electricity system. These emissions are further discussed in Section 5.3.

In the case of CHP systems, in which several plants are feeding the same district heating network, the consequences of the actions are dependent on the merit order of the plants of the system. The merit order is determined by the properties of the plants and the market prices of fuels, electricity, emission allowances, taxes etc. Especially if gas turbine combined cycle (GTCC) CHP plants are replaced, electricity production is decreased due to the high power-to-heat ratio of GTCC. In **Figure 6**, the merit order 2 of Publication VI was used, because it represents the typical existing price levels. However, the merit order is sensitive to prices of fuels (including local taxes), CO_2 emission allowances and electricity.

In the studied CHP case, biomass co-firing increases the CO_2 emissions of CHP system if biogenic CO_2 is also taken into account, but based on the existing regulation, bioenergy is considered as carbon neutral, resulting in a significant decrease in GHG emissions. In reality, impacts of different types of bioenergy uses on the carbon balances of the systems are extremely complex.

In addition to biomass combustion, CO_2 emissions are also caused from biomass harvesting, pretreatment and transportation. The energy density of biomass is typically low in comparison to fossil fuels, unless biomass is refined to liquid biofuels, torrefied biomass or other more valuable products. Due to its low energy density, transportation distances of solid biomass to combustion are typically short in comparison to fossil fuels. The main impact of biomass utilisation on the GHG balance is often the change in carbon stock of soil and growing biomass. This change should be taken into account in emissions reported in the AFOLU sector, as presented by IPCC (2006). Impacts on carbon stock decrease the net reductions in GHG emissions obtained by replacing fossil fuels by biomass. On the other hand, bioenergy is often linked to broad forest management systems, where increased forest growth and carbon bound in timber products should also be taken into account. When bioenergy is obtained from the side streams of forest management and forest industries, allocation of impacts between different wood products and bioenergy may be used. Depending on several variables, the selected reference scenario and especially the considered timeframe, the net impact of bioenergy on GHG emissions can be large or negligible. Net climate impacts of the utilisation of different fractions of biomass are extremely ambiguous and are not the focus of this dissertation.

Even more complex system level impacts occur in the case of CCU concepts (Publication V). Capturing CO_2 from combustion for synthesis decreases direct emissions, by-product oxygen is used to increase the production and efficiency of the CHP plant, increasing direct emissions and production but decreasing system level emissions, and electrolysis consumes electricity, increasing system level emissions. In addition, heat is recovered from the PtG plant for district heating and the produced SNG decreases the consumption of fossil fuels in the transportation sector. These impacts are hardly visible in **Figure 6** because of the small side stream of flue gas CO_2 assumed to be captured and utilised for synthetic fuels in the studied case. However, the concept is scalable to some extent and can be multiplied.

The scale of the PtG plant was selected on the basis of the existing scale of the commercial electrolysers. The scale was not optimised for the integration, i.e. the larger PtG might be more feasible. Optimisation of the dimensioning of the PtG plant would have been challenging, because of several previously mentioned impacts and costs involved. In addition, more valuable synthetic fuels than SNG can be produced.

Even if the CO_2 emissions are physically decreased in the CHP plant due to utilised CO_2, the captured CO_2 may not be subtracted from the operator's emissions, according to the regulation of the EU ETS. Consequently, the synthetic transportation fuel should be considered to be carbon neutral from this perspective, which is also used as a basis for the price of the SNG (Publication V). However, the impacts of electricity consumption on the CO_2 emissions on the system level are important, and are further discussed in Section 5.3. The system level impacts of the PtF on CO_2 emissions are simplified in **Figure 13**.

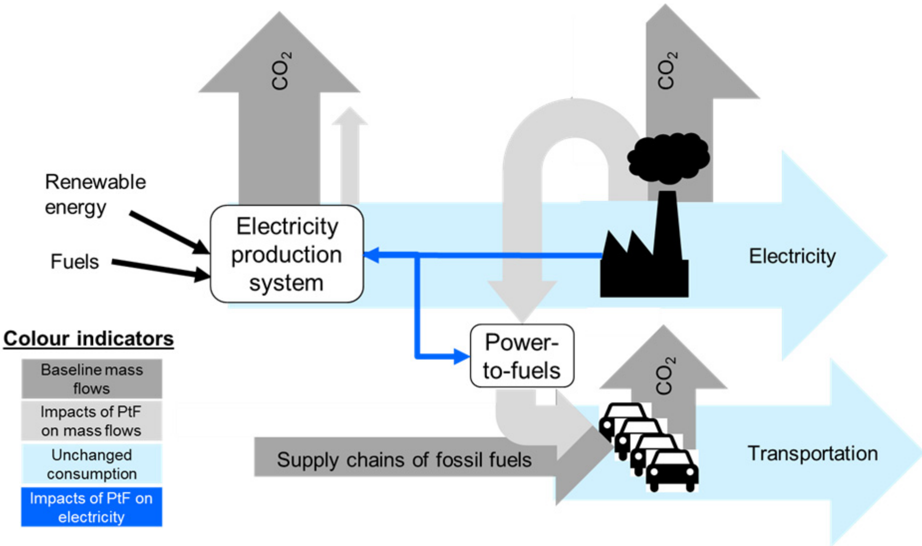

Figure 13. Schematic illustration of the impacts of PtF on CO_2 emissions, which are decreased practically by the amount of the captured CO_2 if the uncertain impacts on electricity production system and supply chains of fossil fuels are excluded. In the EU ETS, the decrease in the CO_2 emissions of the original source is not acknowledged. To avoid double counting, the produced fuel could be considered as carbon neutral. The impact of PtF on CO_2 emissions is typically not dependent on the origin of the CO_2. On the contrary, the impacts on the electricity production system are important, as discussed in Section 5.3.

The synthetic carbon neutral SNG is assumed to be used in the transportation sector due to its high volume, need and price. The volume is high because the results for SNG can also be applied for other hydrocarbons (e.g. methanol, gasoline, diesel), which similarly can be produced from hydrogen and captured CO_2. High price is a consequence of high marginal costs to achieve CO_2 reduction targets (blending mandates) in transportation. Carbon neutrality and consequent high income are key assumptions for CCU concepts. In addition, the marginal cost of achieving the CO_2 emission reduction targets in the overall non-ETS sector is high by comparison with the CO_2 allowance cost in the EU ETS. Therefore it is beneficial for CCU if the CO_2 emission is accounted for ETS sector rather than in non-ETS. The existing regulation concerning accounting for the CO_2 emissions of transportation fuels by CCU is still immature, and is under development in the EU while writing this dissertation.

According to **Figure 6**, the system level emissions are increased in the CCU case, even if it is assumed that CCU decreases an equal amount of CO_2 to that which is captured. The increase is due to the high emission factor used for electricity, which is further discussed in Section 5.3. Equal reduction of CO_2 emissions is justified if the produced synthetic fuels replace similar fossil hydrocarbons. If usage of for example fossil gasoline is replaced by synthetic natural gas, the emission reduction is higher due to the higher CO_2 per energy ratio of gasoline. The avoided emissions from the supply chains of replaced fuels are not included in **Figure 6**, although the electricity consumed for CCU is included. Avoided emissions from production, transportation and refining of replaced fossil fuels might be significant.

Rapid load response of electrolysers enable additional incomes from several electricity markets, for example the FCR. The potential incomes from FCR are significant and might be important to make the investments profitable. However, the size of the FCR market is relatively small, and new actors in the markets may decrease the prices. It is estimated that the demand for FCR may increase in the near future, mainly due to the increasing share of variable renewable energy sources (wind and solar) in the systems.

The N_2O and CH_4 emissions from fluidised bed combustion studied in Publication I are not taken into account in Publications V and VI, which focus on the economic feasibility of the concepts in the EU ETS. As illustrated in **Figure 5**, the importance of N_2O emissions in comparison to CO_2 emissions is minor in these cases. According to Publication I, CH_4 emissions are even less significant in well-functioning large-scale boilers. On the other hand, the relative share of N_2O and CH_4 emissions increases when fossil CO_2 emissions are decreased.

National taxation, subsidies and conditions have significant impacts on the dynamics of the systems and especially on the economic feasibility of different actions. Therefore, the results of the presented Publications should be applied to different regions with care.

5.3 The importance of electricity

The price of electricity is known to be an important factor in terms of economic feasibility of many of the studied concepts. The presented cases also highlight the importance of changes in electricity consumption or production on the system level emissions (“emission factor of electricity”). The impacts presented in **Figure 6** are based on marginal electricity. The power systems are becoming less carbon intensive, and in the future, the CO_2 emission factor of marginal electricity may also be lower. Consequently, the differences between the system level impacts and direct emissions of the studied concepts will decrease.

In addition to marginal electricity, there are also several other possible methods to estimate the impacts of altered electricity consumption or production. The emissions can be estimated based on the type of purchased electricity, for example green electricity products, which are controlled by guarantees of origin. Typically, average emissions of electricity are used. Averages can be defined with different boundaries, for example at the levels of supplying company, country or market. However, the average values do not reflect the consequences to the system resulting from the studied operation. In addition, each of the boundaries is contrived because of imports and exports through the selected boundaries. For example, even if green electricity with guarantees of origin is consumed, the entire power system is impacted.

In the Nordic countries, a reasonable system and market to consider is Nordpool, the combined power market of the Nordic countries. Due to the limitations in electricity transmission between countries, national data may also be justified. On the other hand, even the impacts on the larger electricity system can be studied, including grid connections to, for example, Russia and Central Europe. Due to the relatively low average CO_2 emission intensity of electricity in Nordpool (and also in Finland) compared to electricity production by fossil fuels, the difference between the CO_2 intensity of average electricity (attributional approach) and marginal electricity (consequential approach) is highlighted.

This difference can lead to opposite conclusions when the emission reductions of different concepts are compared.

If a longer timeframe is considered, the altered electricity consumption or production has some impact on the profitability of potential new investments in electricity production capacity and consequently on emissions. This is one possible rebound impact typically excluded from the studies. Even more apparent and significant rebound impact comes from the fixed cap of emission allowances in the EU ETS, which is discussed in Section 5.4.

None of the previously presented approaches to determine the emission factor of electricity is absolutely correct, but selection of this single parameter for the system level studies has a major impact on the results of several presented cases. A strong influence for CO_2 emissions from CHP in comparison to other heating systems is illustrated in **Figure 14** of Section 5.5. In general, an emission factor for electricity is needed in most LCA studies, carbon footprints and other indicators taking into account broader systems than direct emissions from a single operator.

For example, if the system level CO_2 emissions of the studied OBF concept with CCS are evaluated with the average CO_2 emissions reported for electricity production in Finland in 2017, namely 89 kg/MWh (Finnish Energy, 2017) instead of for marginal electricity (850 kg/MWh), the overall impact on emissions decreases by 46%. With the average emission factor for electricity, the high efficiency WtE concept with coal co-firing leads to the highest GHG emissions among the compared options, although the same concept resulted in the lowest emissions in **Figure 6**. The impact is opposite for CCU concepts based on electrolysis. In **Figure 6**, the studied PtF concept increased the system level GHG emissions because marginal electricity was used. With a lower emission factor for electricity, overall emissions can be decreased.

One rationale for PtF solutions is also the fact that flexible electrolysis and synthetic hydrocarbons admit more variable renewable energy sources (solar and wind) to the markets, because the concept can be used as a seasonal energy storage. If investment in PtF results in increased production of renewable electricity, assessing the impacts solely on the basis of the carbon intensive marginal electricity of the existing system is misleading. The consequences of electric vehicles are similar, excluding the suitability for seasonal storage.

The emission factor used for marginal electricity (850 kg/MWh) is not even the highest justified emission factor for electricity. Because the grids are integrated, it can be assumed that the marginal type of production has lower efficiency than is typical for state-of-the-art power plants. If for example peat or brown coal is used as a fuel of marginal power production in plants with moderate efficiency, the emission factor of electricity can be over 1000 kg/MWh. In addition, if emissions of fuel supply chains are added, even higher emission factors are justified (Publication II). Marginal approach highlights for example the importance and effectiveness of energy-saving options, which are underestimated if average values are used.

5.4 Impacts under the fixed cap of the EU ETS

EU ETS is a cornerstone of the EU climate policy. Despite this, the apparent rebound impact of any emission reduction action under the EU ETS, namely the release of emission allowances for other operators, is often ignored in system level studies. Taking into account the impacts on emission allowances is the most fundamental methodological choice discussed in this dissertation, having a crucial impact on the effectiveness of several concepts.

A cap and trade system such as the EU ETS is a powerful tool to cost efficiently decrease emissions within a broad system boundary such as the EU. The problems of the EU ETS have been widely discussed, but the basic reason has not been the mechanism, but simply the too loose target. The loose target combined with an economic down-term in Europe has led to a significant surplus of emission allowances in the markets and a low price of emission allowances. Another problem, or a consequence of the loose target, has been the overlapping of national and voluntary actions. These actions have released emission allowances to the markets and further decreased the price of allowance.

However, from the perspective of total CO_2 emissions, the price of allowances is not important but their total amount is. The price is important for the operators, technology suppliers and investments. From their point of view, the EU ETS has not been functioning, but the GHG emissions have actually decreased faster than the set target. The difference between the target and actual emissions is the surplus of emission allowances.

Taking into account the impacts on the emission allowances in the EU ETS leads to results in which only the impacts on emissions not covered by the EU ETS (non-ETS sector) are relevant. These impacts include for example electricity imports and exports from/to regions not covered by the EU ETS (e.g. Russia), impacts on transportation, fuel supply chains, waste management (incl. WtE in most of the EU member states) and small-scale boilers.

Applying this approach to CCU, synthetic fuels from CO_2 and hydrogen made by electrolysis can be justifiably carbon neutral if the origin of CO_2 belongs to EU ETS and the electricity consumed due to electrolysis impacts on the production covered by EU ETS. The climate impact is independent of the source of CO_2 (whether it is biogenic or fossil) or what kind of electricity is purchased for the electrolysis from the power system. The impact of CCU-based fuels on CO_2 emissions is similar with electric vehicles, but the efficiency of the electric vehicle-based system is better. Therefore, transportation fuels through electrolysis and CCU can be classified as indirect electrification of the transportation sector (electrofuels). Depending on the type of electrofuels, these require none or lower investments in vehicles but higher investments in fuel production in comparison to electric vehicles.

If the captured CO_2 is used for transportation of fuels, and operations under the EU ETS are impacted by capturing CO_2 and used electricity, emission allowances from the cap of EU ETS are consumed and usage of fossil fuels in the non-ETS sector is decreased. Consequently, the fixed cap of EU ETS remains unchanged and the emissions of non-ETS are effectively decreased. From this perspective, CCU for transportation fuels is a powerful tool in climate change mitigation in the EU. This is a totally opposite conclusion to the results obtained by calculating the impacts based on the emission factor of marginal electricity.

Rebound impacts under the EU ETS became even more complex after the EU ETS reform agreed in 2018 (EC, 2018). This is because of the emphasised role of the Market Stability Reserve (MSR) of the EU ETS. The idea of the MSR is to address the current surplus of allowances and to improve EU ETS resilience by adjusting the supply of allowances. The MSR will make the allowance price more stable but simultaneously it makes the impact assessment of any actions under the EU ETS very difficult. This is because the amount of allowances moved to MSR is dependent on the total number of allowances in circulation in the EU ETS, i.e. on the actions of all the operators under the EU ETS. Therefore the impact of the studied activity may, or may not, impact on the allowances moved to MSR. If these allowances are later released from MSR, the corresponding amount of CO_2 emissions is not avoided but only delayed. However, based on the recent reform of the EU ETS it is also possible that a share of the allowances from MSR are cancelled (ibid.). In this case, the share of the allowances moved to MSR actually becomes avoided emissions. Consequently, any activity which influences the number of allowances in circulation may affect the number of allowances cancelled from MSR. Contrary to previously presented arguments against ineffective overlapping of national and voluntary actions, cancellation of the allowances from MSR may make these actions effective.

However, MSR may be effective only temporarily, whereas EU ETS is set to continue as a cornerstone of EU climate policy. The target of EU ETS will be more ambitious in the 4th Phase (2021-2030), resulting in 43% reduction of emissions compared to 2005 and an even faster decline of emissions has been discussed. After the cancellation of allowances from MSR in 2023, the target of Phase 4 of the EU ETS should be ambitious enough to avoid a surplus of allowances. Therefore, the most reasonable boundary in the impact assessments related to the near future is probably that taking into account the fixed cap of allowances in the EU ETS. Consequently, the assessments should focus on the impacts on the non-ETS sector. However, the discussion on the possible rebound impacts can be continued even further. For example, if national and voluntary emission reduction actions lead to a surplus of emission allowances in the EU ETS, a rebound impact on political decisions, for example on more ambitious targets of the EU ETS, or another cancellation of emissions allowances from MSR are possible.

5.5 Examples with different boundaries

The previous discussion on the complexity of the impacts and the importance of the boundaries is summarised in **Table 3** using electrofuels and electric vehicles as examples.

Table 3. Electrofuels and electric vehicles as qualitative examples of complex impacts on CO_2 emissions

Boundary extension ↓

Boundary		Electrofuels	Electric vehicles
Direct CO_2 emissions from a car		Similar to fossil substitutes (gasoline, diesel, etc.)	Zero emissions
Local systems	Purchased green electricity	Zero emissions [1)]	Zero emissions
	Average CO_2 emissions	Moderate emissions (in Nordic countries)	Minor emissions (in Nordic countries)
	Marginal electricity	High emissions	High emissions
	Impacts on future investments	Unknown impacts	Unknown impacts
EU ETS	Fixed cap of the EU ETS	Zero emissions	
	Impacts on electricity imports/exports from regions not covered by EU ETS	High emissions (if not taken into account that both of these options enable more renewables in local systems)	
	Market stability reserve (MSR) and possible cancellation of allowances from MSR	Unknown impacts (depending on the development of the entire EU, regulation and CO_2 emissions)	

1) If the utilised CO_2 is accounted for the original source as in the EU ETS.

In addition to the complexity presented in **Table 3**, other phases of the life cycles also add complexity to the impacts. For example, manufacturing of the needed equipment, raw materials and chemicals may have a significant role in some cases. The importance of other phases is highlighted in the cases where direct emissions are low. Furthermore, other environmental impacts than climate change are also important to consider. Because all the direct pollutants (particles, NOx, SOx…) are avoided in the case of electric vehicles, the investment is well justified from the environmental perspective.

The system boundaries presented in **Table 3** can also be applied for other concepts. For example, the efficiency of CHP in terms of climate change mitigation can be compared with electricity-based heat sources (electric heaters, boilers and heat pumps) using the same boundaries as in **Table 3**. The comparison is interesting, because CHP is often operated according to heat demand, i.e. consumption of heat increases electricity production in the system. By contrast, in the case of electricity-based heat sources, heat consumption increases electricity consumption. Consequently, the importance of the emission factor assumed for electricity is emphasised in the comparison between the CHP and electricity-based heat sources. From this perspective, heat pumps are similar to electric heating, but the electricity consumption of the heat pumps is lower, according to the coefficient of performance (COP) of the heat pumps.

In **Figure 14**, the CO_2 emissions allocated to heat in the CHP cases studied in Publication VI without CCS/U are presented as a function of emission factor for electricity. The allocation is made by decreasing the emissions of produced electricity from the overall CO_2 emissions of the CHP plant. There are also several other possible allocation methods, which would lead to different results. However, other methods are not considered reasonable in this context. In addition, the CHP plants are not always operated based only on the heat demand, which significantly affects the consequences of the altered heat consumption. The operation can be influenced for example by the electricity price, depending on the technical solutions existing in the plant (Publication V and Publication VI).

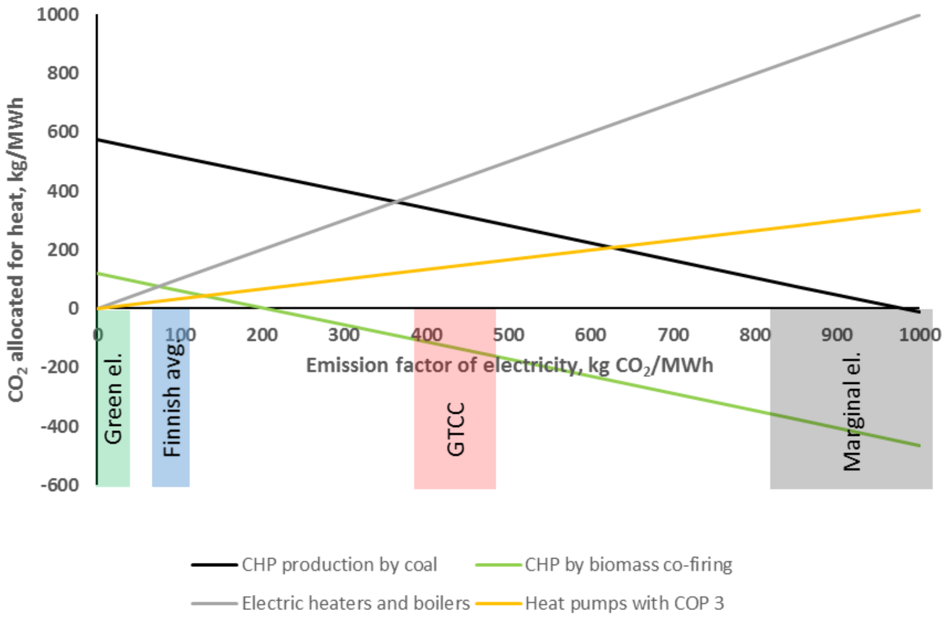

Figure 14. The sensitivity of CO_2 emissions allocated for studied CHP cases (without CCS/U) and comparison with electricity-based heating solutions as a function of an emission factor for electricity. The emission factor for electricity is dependent on e.g. the region, time and chosen system boundaries. In the Figure, green electricity (product-based boundary), average emissions of electricity production in Finland, gas turbine combined cycle (GTCC) and coal-based marginal electricity are used as examples of numerous possible approaches and boundary definitions for the impacted system.

As illustrated in **Figure 14**, selection of one single factor (emission factor of electricity) in the approach defines the result of the comparison between the CHP-based heating and heat pumps. Electricity-based heating solutions result in lower CO_2 emissions than CHP cases if lower emission factors are assumed for the electricity. If the consequences in the power system are considered from the perspective of marginal production, CHP cases result in lower CO_2 emissions. With the used approach, CO_2 emissions allocated for heat become negative if bioenergy is accounted carbon neutral and CO_2 intensive electricity is replaced by the produced electricity. This includes the perspective that the additional electricity production by the CHP plant is a consequence of heat consumption.

As discussed in Section 5.3, the electricity system is developing less carbon intensive, which will also decrease the carbon intensity of marginal electricity in the future. However, the carbon intensity of electricity within the EU ETS is not important in comparison, if the fixed cap of the EU ETS is taken into account. By contrast, the importance of the consequences on electricity imports and exports is emphasised.

Potential impacts on imports and exports are important arguments for CHP over the heating solutions that consume electricity. This is because increasing CHP probably decreases emissions elsewhere, due to increased electricity exports or decreased imports, whereas the impact of additional electricity consumption is the opposite. However, the assessments regarding the broader systems include more parameters, which are dependent on the choices of other actors influencing the system, including politicians and legislators, who can make decisions which significantly change the consequences of studied actions, e.g. emissions of heating solutions on system level.

5.6 How to influence climate change mitigation?

Because of the previously presented crucial impacts of the approach and system boundaries, it might be confusing for the public to understand how to influence climate change mitigation. Different actors have different ways to contribute. Because the problem is global, solving climate change requires international agreements. The objective of the Paris Agreement is clear, but more specific regional regulations and actions are needed to achieve this objective. Currently global GHG emissions are not on a pathway to achieve the objectives of the Paris Agreement.

Because the cap of the EU ETS defines the GHG emissions of the EU ETS sector, it is essential that the cap is decreased fast enough. Currently, even after the latest reform of the EU ETS agreed in 2018 (EC, 2018), the decrease rate is too slow from several perspectives. The historic emissions and economic welfare of EU would justify faster reductions, the prices of emission allowances proves that low cost options are available, and the demonstration of exportable new technologies would benefit from market-based demand. Because EU member states, organisations and companies can only perform ineffective overlapping actions within the EU ETS, the policy makers in the EU parliament and the council have the control and the responsibility to take the necessary actions. However, after the reform of the EU ETS in 2018 (EC, 2018), the overlapping actions may also have an effect if executed before 2023, as discussed in Section 5.4.

It is also essential to avoid carbon leakages, i.e. the increase of emissions in less regulated regions or business areas because of mitigation actions in the regulated areas. One mechanism to avoid carbon leakages is allocation of free emission allowances in the EU ETS for industries with a risk of carbon leakage. Free allocation does not affect the total amount of emission allowances and therefore it is not essential in terms of overall emissions of the EU ETS sector, but it does decrease the risk for carbon leakage even if the amount of carbon leakage is difficult to estimate.

Carbon leakage is not limited only to the possible impacts on geographical location of the new investments. Carbon leakage may also take place due to increased product prices which have unavoidable impacts in the markets. The possible consequences are that the production rates under the EU ETS decrease and production outside EU ETS increases. Therefore, any action increasing the production costs in the EU increases the risk of carbon leakage. Consumers and companies can avoid carbon leakages by avoiding buying of consumables produced outside the EU.

National and voluntary actions should focus on the non-ETS sector. In the non-ETS sector, effective actions are for example to decrease fossil fuel consumption in transportation and household scale heating, as well as the actions related to agriculture. In the EU, activities could also be moved from non-ETS to the EU ETS, because the marginal cost of emissions reductions in the non-ETS is significantly higher. For example, WtE plants were included in the EU ETS in Denmark and Sweden. The same decision could be made by the policymakers of other member states or by EU-wide regulation. Transportation fuels can be included in the EU ETS by adding the cost of CO_2 emission allowance to the fuel price. From monitoring perspective this would be simple and precise, because the carbon content of homogenous transportation fuels is well known and fuel flows are already measured in several points of the supply chains.

The taxes related to consumption could be increased and the CO_2 allowance cost added to the products (including electricity) imported from regions not covered by the EU ETS. CO_2-based taxes are justified when related to consumption, such as burning the fuels (e.g. the tax included in gasoline price). By contrast, fixed annual CO_2 taxes, for example the vehicle tax in Finland (Trafi, 2018), have only a weak connection with real impacts on CO_2 emissions and could be changed to a consumption-based taxes (e.g. added to fuel tax).

Several options for effective non-ETS emission reductions are already economically feasible for general citizens. These include for example changing oil- or gas-based household scale boilers to heat pumps or district heating, utilisation of waste-based biogas and replacing meat by vegetarian food. The reasons why economically feasible options are not mushrooming would be important to understand and overcome.

In Western countries, the most important and cost-effective action is to start rationalising consumption in general. This does not mean decreasing the welfare of societies, which should even improve if the money is not spent on unnecessary impulse purchases and shopping. The positive impacts of the actions saving resources are also often more certain than the impacts of replacing one consumption by another. However, the money saved due to rationalised consumption or improved efficiency should be used with care in order to avoid rebounding to emissions from alternative consumption, such as travelling. One important influence is also created by the examples and education which we give to the next generation with regard to consuming and considering the impacts of everyday actions.

Effective mitigation methods also include decreasing deforestation and increasing carbon sinks. The sinks can be increased for example by afforestation. There is a general willingness for afforestation, but business models should be created to realise the large potential in areas where truly additional carbon sinks can be created. The technology to irrigate for example deserts using solar energy exists, but major investments are required.

Overall, there are hundreds of possible effective actions to mitigate climate change. The technologies for up to 100% renewable energy and carbon-free systems exist, but there is no business case for operators to invest in such a system. To support the truly additional actions in climate change mitigation, the impacts on the emissions from surrounding systems should be taken into account. In addition, the costs and economic benefits can be analysed with broader perspectives. For countries importing a lot of energy, such as Finland, the benefits of renewable energy, energy efficiency and other climate change mitigation options should also be evaluated taking into account the impacts on the balance of trade, energy security, employment, health care costs and other positive consequences. Because high costs often mean high employment, different boundaries also lead to opposite conclusions in the cost analysis. Companies evaluate the costs and benefits from their perspectives. Therefore, policy makers should make the benefits for society favorable to companies, for example by suitable subsidies and taxes.

Investors can influence by investing in clean technologies in the regions not covered by the EU ETS and in the non-ETS sector. Some investors already have for example emission performance limits in their terms of funding. Governments can influence by funding demonstrations and by large investment subsidies for new technologies. There are thousands of innovations regarding low carbon solutions, but commercialisation is slow due to technological and economical risks related to the new technologies, as well as the uncertain political framework. Companies are often conservative, and people tend to avoid personal risks in their decisions at work and at home. The concern over climate change is general, but actions are minor and rare. The risks related to investments in new technologies are reflected in higher requirements for the returns on investment, or shorter required payback time. A small step out from a personal comfort zone at work and at home could make a huge difference if generally applied.

It is important to truly consider the objective and to choose the tools accordingly. If the objective is to mitigate climate change, global GHG emissions need to be decreased. For this objective, a broad cap and trade system, with a low cap, is a good mechanism. If the objective is to encourage new investments in solar and wind power, investment subsidies are effective tools. If the objective is to get rid of coal, denial of coal is the most effective mechanism. Finally, if the objective is to get new clean technologies on the markets, public funding for demonstration of these technologies in several scales is often required.

6. Conclusions and recommendations

The need to accelerate the actions to mitigate climate change is urgent. It is irresponsible to delay, because the later actions are taken, the greater will be the damage. Furthermore, later actions also lead to higher overall costs of mitigation and adaptation. Above all, the consequences and costs of climate change will be suffered mostly by future generations, who cannot defend themselves against the inefficient and consuming lifestyles of our generation.

Because climate change is a global problem, the impacts of actions and decisions should be considered from a global perspective. This means broad system boundaries leading to ambiguous selections in the assessments. In Europe, EU ETS is used as a cornerstone of the climate policy to guarantee achievement of the emission reduction target in the broad (EU-wide) system. Although the EU ETS is a cornerstone of EU's climate policy, it is often ignored when the impacts on the system level GHG emissions are studied. As presented in Sections 5.4 and 5.5, taking into account the impacts on available CO_2 emission allowances can lead to opposite results to those in studies in which the impact is ignored.

Most of the studied concepts enable large decreases in emissions if only the direct fossil GHG emissions are considered (**Figure 5**). The results show that the system level impacts on GHG emissions significantly differ from direct emissions, typically hindering the benefits of the concepts in terms of emission reductions (**Figure 6**). Especially, the impacts on the electricity production system are important.

Currently, the system level impacts of altered electricity production or consumption are often estimated using average GHG emissions of the system, which is misleading in many contexts. In reality, the consequences in the system are complex and dependent on numerous issues, for example the considered timeframe. Average production is not reacting to considered changes, but marginal production is. Due to the relatively low average CO_2 emission intensity of electricity in Nordpool, the difference between the GHG intensity of average electricity and marginal electricity is highlighted. However, under the EU ETS, the limited amount of emission allowances is more important. In addition, several other system level impacts can also be taken into account. For example, new investments can be predicted to be less carbon intensive than the existing marginal electricity, decreasing the emissions of future systems.

A good example highlighting the importance of the electricity system and the EU ETS is the studied PtF concept (Publication V). Such concepts, in which CO_2 is captured and utilised as transportation fuels using synthesis with hydrogen from electrolysis, may be economically feasible in realistic future markets. The economic feasibility is also strongly dependent on the regulation concerning whether the electrofuel is classified as renewable or not. As presented in Section 3.2, the CO_2 utilised for transportation fuels (i.e. in the non-ETS sector) is accounted for the original source if captured from the plant operating under the EU ETS. Consequently, the emission should not be double-counted in a non-ETS sector. From this perspective, the synthetic fuels from captured CO_2 do not differ from electric vehicles, independently of whether the CO_2 originates from biomass, fossil fuels or carbonates of industrial processes. However, the differences in the impacts on power systems are significant.

Electrofuels can be utilised as seasonal energy storages, helping in decarbonising the power sector. As highlighted in Section 5.4, increasing electrofuels (and electric vehicles) in the transportation sector would not increase the CO_2 emissions of the EU ETS (because the limited amount of allowances) but would significantly decrease the emissions accounted for the transportation sector. The consequences of the changes in imported/exported electricity for the GHG emissions from electricity and fuels produced outside the EU may be considerable. Taking into account the fixed cap of EU ETS, the impacts on electricity imports and exports are probably the most important truly additional impact in the case of many activities within or overlapping the EU ETS.

As illustrated in **Figure 8** - **Figure 12**, most of the concepts studied in this dissertation are not yet economically feasible. The examples of economically feasible concepts are biomass co-firing and CHP. The potential of CHP is important, because half of the energy consumed in the EU is used for heating. In addition, it is possible to combine other heat sources to CHP systems, such as solar heat when available. Similarly, the waste heat from PtF processes can be recovered in district heating networks.

Based on the presented results and conclusions, it is recommended to consider broader systems (in Europe especially the EU ETS) in the decisions aiming for climate change mitigation. It is important to keep in mind that the uncertainties in the system level studies can be significantly greater than those related to emissions and economic feasibilities studied from one operator's point of view. The importance of the EU ETS also sets the responsibility for policy makers. In the sectors covered by the EU ETS, a truly additional reduction in CO_2 emissions can be achieved by permanently decreasing the amount of available emission allowances. The decrease should be faster than the currently decided rate.

As highlighted in Section 5.4, actions overlapping with the EU ETS are often inefficient in terms of costs and reductions of CO_2 emissions. Mechanisms such as MSR and potential cancellation of allowances from MSR temporarily change the impacts of overlapping actions. Simultaneously, cancellation of surplus allowances from MSR make the impact assessment for any activity dealing with the EU ETS extremely uncertain. This is because in addition to studied activity, other activities connected to EU ETS (e.g. consuming electricity in Europe) impact on surplus of allowances to be cancelled.

In addition to faster decrease of emission allowances in the EU ETS, the emphasis should be placed on avoiding potential carbon leakages, including impacts of electricity imports and exports. For industries such as the studied steel mill, the existing mechanism to avoid carbon leakage is allocation of free CO_2 emission allowances. Additional effective mechanisms could be for example to introduce carbon taxes for products, raw materials and electricity imported to the EU.

National policies and voluntary actions should focus on decreasing emissions from the non-ETS sector. The impacts of fundamental actions are more certain than those of complex scenarios. Rationalising irresponsible consumption in general is economically the most feasible option. This can be guided by taxation, also facilitating the fiscal balance. There are also other economically feasible low-carbon and domestic options available for the non-ETS sector, such as transportation and food. Consequently, simultaneous savings in emissions and costs are available.

Finally, even a carbon-neutral society is possible. Technological options are not a barrier, but actions are required.

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ERRATA:

Publication IV: Equation 2 was corrupted during the publication process of the article. The correct formula is

$$\frac{Capex_{CCS} + OtherOPEX_{CCS}}{SteelProd.} + P0_{Steel} + E_{CCS} \times P0_{Electricity} + P_{CO2} \times (correlation \times E_{total} + CO_{2,total})$$

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Despite international agreements, global greenhouse gas (GHG) emissions have not decreased according to the targets. Consequently, our generation is creating an enormous problem for future generations. As climate change is a global problem, GHG emissions must decrease globally. This dissertation examines the impacts of major emission reduction solutions with different system boundaries, highlighting the importance of boundary selection on the results. In addition, the economic feasibilities are evaluated.
The case examples represent the most important sectors in terms of global CO_2 emissions, such as electricity and heat production, the steel industry and transport. The studied technologies include efficient Waste-to-Energy (WtE) concepts with high power-to-heat ratio, utilisation of CO_2 Capture and Storage in different applications, replacing steel mill blast furnaces with Oxygen Blast Furnaces, Combined Heat and Power, and Carbon Capture and Utilisation for storable fuels, which can also be used for transportation.

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