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Assessing the uncertainties of climate policies and mitigation measures

Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments

Sampo Soimakallio

VTT SCIENCE 11

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Assessing the uncertainties of climate policies and mitigation measures

Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments

Ilmastopolitiikkatoimien ja päästövähennysten epävarmuuksien arviointi. Näkemyksiä biopolttoaineiden tuotannosta, verkkosähkön kulutuksesta ja päästövähennysvelvoitteiden taakanjaosta. **Sampo Soimakallio.** Espoo 2012. VTT Science 11. 78 p. + app. 80 p.

Abstract

Ambitious climate change mitigation requires the implementation of effective and equitable climate policy and GHG emission reduction measures. The objective of this study was to explore the significance of the uncertainties related to GHG emission reduction measures and policies by providing viewpoints on biofuels production, grid electricity consumption and differentiation of emission reduction commitments between countries and country groups. Life cycle assessment (LCA) and macro-level scenario analysis through top-down and bottom-up modelling and cost-effectiveness analysis (CEA) were used as methods. The uncertainties were propagated in a statistical way through parameter variation, scenario analysis and stochastic modelling.

This study showed that, in determining GHG emissions at product or process level, there are significant uncertainties due to parameters such as nitrous oxide emissions from soil, soil carbon changes and emissions from electricity production; and due to methodological choices related to the spatial and temporal system boundary setting and selection of allocation methods. Furthermore, the uncertainties due to modelling may be of central importance. For example, when accounting for biomass-based carbon emissions to and sequestration from the atmosphere, consideration of the temporal dimension is critical. The outcomes in differentiation of GHG emission reduction commitments between countries and country groups are critically influenced by the quality of data and criteria applied. In both LCA and effort sharing, the major issues are equitable attribution of emissions and emission allowances on the one hand and capturing consequences of measures and policies on the other. As LCA and system level top-down and bottom-up modelling results are increasingly used to justify various decisions by different stakeholders such as policy-makers and consumers, harmonization of practices, transparency and the handling of uncertainties related to methodological choices, parameters and modelling must be improved in order to avoid conscious misuse and unintentional misunderstanding.

Keywords greenhouse gas emission, biofuel, electricity, effort sharing, uncertainty

Ilmastopolitiikkatoimien ja päästövähennysten epävarmuuksien arviointi
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[Assessing the uncertainties of climate policies and mitigation measures – Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments]. **Sampo Soimakallio.** Espoo 2012. VTT Science 11. 78 s. + liitt. 80 s.

Tiivistelmä

Kunnianhimoiset tavoitteet ilmastonmuutoksen hillitsemiseksi edellyttävät tehokkaiden ja oikeudenmukaisten ilmastopolitiikka- ja päästövähennystoimenpiteiden toteuttamista. Tämän tutkimuksen tavoitteena oli analysoida kasvihuonekaasupäästöjen vähentämiseen liittyvien keinojen ja politiikkatoimenpiteiden epävarmuuksia tarkastelemalla biopolttoaineiden tuotantoa ja verkkosähkön kulutusta sekä päästövähennysvelvoitteiden taakanjakoa maiden ja maaryhmien välillä. Menetelminä käytettiin elinkaariarviointia, makrotaloustason skenaarioanalyysia ja kustannustehokkuusanalyysia. Epävarmuuksia tarkasteltiin tilastollisten menetelmien avulla mm. parametrien oletuksia vaihtelemalla, skenaarioanalyysilla ja stokastisella mallintamisella.

Tulokset osoittavat, että tuote- tai prosessitasolla biopolttoaineiden tuotannon ja verkkosähkön kulutuksen kasvihuonekaasupäästöihin liittyy merkittäviä epävarmuuksia, joita aiheutuu arvioinnissa käytettävistä parametrioletuksista, esimerkiksi maaperän typpioksiduulipäästöille ja hiilivaraston muutoksille sekä sähköntuotannon päästöille. Epävarmuuksia aiheutuu myös tarkastelujen rajauksista ja allokointikäytännöistä sekä mallinnukseen liittyvistä tekijöistä, kuten biomassan hiilen vapautumisen ja sitoutumisen välisen ajallisen esiintymisen käsittelemisestä. Maa- tai maaryhmätasolla päästövähennysvelvoitteiden taakanjaossa sovellettavat kriteerit ja tietopohja ovat kriittisiä tulosten kannalta. Sekä elinkaariarvioinnissa että taakanjaossa päästöjen ja päästövähennysvelvoitteiden oikeudenmukainen kohdentaminen ja kerrannaisvaikutusten arvioiminen ovat keskeisiä tekijöitä ja voivat edellyttää useiden erilaisten menetelmien käyttämistä. Elinkaariarvioinnin ja järjestelmätason mallinnuksen tuloksia käytetään enenevässä määrin erilaisten päätösten perusteena. Tarkoitushakuisen väärinkäytön ja tarkoituksettomien väärinymmärrysten välttämiseksi on erittäin tärkeää, että elinkaariarviointiin ja järjestelmätason mallinnukseen liittyviä käytäntöjä yhtenäistetään, tulosten ja oletusten läpinäkyvyyttä lisätään ja menetelmiin, parametreihin ja mallinnukseen liittyvien epävarmuuksien käsittelyä parannetaan.

Avainsanat greenhouse gas emission, biofuel, electricity, effort sharing, uncertainty

Preface

It was the spring of 2000, when I started my career as a scientist at VTT Technical Research Centre of Finland. In the early stages my work was mainly related to a techno-economic assessment of abatement of fluorinated greenhouse gases. Since then I have participated in many projects regarding greenhouse gas impacts related to energy systems, in particular bioenergy systems. I have also become familiar with various measures for differentiating emission reduction targets between nations. The ideas and papers in this thesis have been generated over many years and result from several public research projects. I kindly thank all the funding organizations involved (see acknowledgement for details). The processing of the two latest papers and this summary was funded by VTT, and my gratitude goes especially to Vice President Kai Sipilä and Technology Manager Seppo Hänninen.

I express my greatest gratitude to the Climate Change Research Group of VTT. I thank especially Professor Ilkka Savolainen, who acted as an instructor of this thesis, for his support, motivation and guidance throughout the last 12 years. I also wish to thank Professor Sanna Syri for her support, encouragement and guidance. She is a former member of the Group and my former line manager, and she acted as a supervisor of this thesis. Furthermore, I would like to highlight the role of Dr Kim Pingoud and Mikko Hongisto, who have both taught me a great deal regarding methodologies for determining greenhouse gas emissions in various contexts during these years. I am also grateful to all the other – former and current – Group members for a vast number of fruitful conversations and collaboration related to climate change mitigation in its all comprehensiveness.

I would like to thank the pre-examiners of my thesis, Professor Kornelis Blok and Professor Ander Hammer Strømman for their dedication and valuable comments on my thesis. Naturally, the co-authors of my thesis played a significant role. Every one of them have taught me something special. Consequently, I would like to express my warmest gratitude to; Tommi Ekholm, Juha Kiviluoma, Kati Koponen, Tuula Mäkinen, Teuvo Paappanen (who unexpectedly passed away in 2011) and Professor Ilkka Savolainen (VTT), Dr. Laura Saikku and Dr. Hannu Mikkola (University of Helsinki), Dr. Katri Pahkala (MTT Agrifood Research Finland), Professor Sanna Syri (Aalto University) and Dr. Niklas Höhne and Sara Moltmann (Ecofys GmbH).

I would like to acknowledge numerous other colleagues in particular at VTT, Finnish Environment Institute SYKE, MTT Agrifood Research Finland, Finnish Forest Research Institute (Metla), The Government Institute for Economic Research (VATT), University of Helsinki, Statistics Finland, the Finnish Ministry of the Environment, the Ministry of Employment and the Economy and IEA Bioenergy Task 38 network for fruitful collaboration and many interesting and pleasant discussions throughout these years. Also, the people at the Energy Systems knowledge centre of VTT not least for the in many ways useful and enjoyable coffee breaks are gratefully acknowledged. For valuable assistance in drawing Figure 2 of the thesis, I would like to thank Kati Koponen and Sébastian Piquemal.

Furthermore, I would like to thank all my dear friends outside my work. The many amusing things that have happened, and the unique time which we have spent together, especially those of my friends who are involved in Hissien Ystävät ry, are something totally indispensable. Tennis and floorball have been my dearest hobbies for a long time. I am really happy to have had an opportunity to get to know many very nice people off and on the tennis courts for almost 30 years. The same holds true of floorball, in which the Hanat Auki ry team with all the former and current members have played an important role in my life for more than 15 years.

Finally, I would like to thank all my dear family and relatives, especially my wife Laura, parents Ulla and Anssi, brother Mikko (and family) and my parents-in-law Marjatta and Olli. In particular, my parents Ulla and Anssi have supported me unstintingly all these years. Despite their endless love and support, I think they did not believe that I would ever do this. Never mind, neither did I. But then I got to know Laura. It was autumn 2007 when we met for the first time in the Finnish Ministry of the Environment. (In the meanwhile I would like to thank retired Senior Environmental Adviser Jaakko Ojala for unintentionally bringing us together). Laura encouraged me to publish some of my work in scientific journals. She helped me a great deal in getting to know how papers should be produced. Later I became totally inspired with writing papers and became more confident that I would write this thesis someday. Two very special and important places can be highlighted; the dear winter holiday house Monomaja in Äkäslompolo and our own home in Kruununhaka. Both of them have played an invaluably important role in the creation and writing process of the last three papers and this summary. Besides being my dear and loving wife and the joy of my life, Laura really inspired and encouraged me to write this thesis. It is impossible to express here how grateful I am to her.

Espoo, June 2012
Sampo Soimakallio

Academic dissertation

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Opponent	Professor Markku Ollikainen Department of Economics and Management University of Helsinki

List of papers

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

I **Soimakallio, S.**, Mäkinen, T., Ekholm, T., Pahkala, K., Mikkola, H., Paappanen, T. 2009. Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland – Dealing with the uncertainties. Energy Policy 37(1), 80–90.

II **Soimakallio, S.** & Koponen, K. 2011. How to ensure greenhouse gas emission reductions by increasing the use of biofuels? – Suitability of the European Union sustainability criteria. Biomass & Bioenergy 35, 3504–3513.

III **Soimakallio, S.**, Kiviluoma, J., Saikku, L. 2011. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) – A methodological review. Energy 36, 6705–6713.

IV **Soimakallio, S.**, Saikku, L. 2012. CO_2 emissions attributed to annual average electricity consumption in OECD (the Organisation for Economic Co-operation and Development) countries. Energy 38(1), 13–20.

V Saikku, L. & **Soimakallio, S.** 2008. Top-down approaches for sharing GHG emission reductions: uncertainties and sensitivities in the 27 European Union Member States. Environmental Science & Policy 11(8), 723–734.

VI Ekholm, T., **Soimakallio, S.**, Moltmann, S., Höhne, N., Syri, S. & Savolainen, I. 2010. Effort sharing in ambitious, global climate change mitigation scenarios. Energy Policy 38(4), 1797–1810.

Author's contributions

In **Paper I**, Sampo Soimakallio is the main author. Sampo Soimakallio structured the paper, selected the methodological choices, collected the greenhouse gas emission and uncertainty data and created the assessment model in MS Excel software. Tuula Mäkinen planned the research questions, provided data on the ethanol process and commented on the paper. Tommi Ekholm carried out the Monte Carlo simulations. Density functions for parameters were jointly selected by Tommi Ekholm and Sampo Soimakallio. Hannu Mikkola and Teuvo Paappanen provided data on the energy use of agricultural and forest machinery, respectively. Katri Pahkala provided data on agrochemical use and agricultural yield rates.

In **Paper II**, Sampo Soimakallio is the main author. The analysis was jointly planned by Sampo Soimakallio and Kati Koponen. The paper was structured and written by Sampo Soimakallio. Kati Koponen collected the data for the literature research, wrote the supplementary information and commented on the paper.

In **Paper III**, Sampo Soimakallio is the main author. The analysis was planned by Sampo Soimakallio and Juha Kiviluoma. The paper was structured and written by Sampo Soimakallio. Juha Kiviluoma and Laura Saikku commented on the paper.

In **Paper IV**, Sampo Soimakallio is the main author. The paper was co-written by Sampo Soimakallio and Laura Saikku. The calculations were carried out by Sampo Soimakallio. The GHG emission intensity analysis was carried out by Sampo Soimakallio and the country level emission leakage analysis by Laura Saikku. The data was jointly collected by Sampo Soimakallio and Laura Saikku.

In **Paper V**, the data was jointly collected and analysed and the manuscript co-written by Laura Saikku and Sampo Soimakallio. Laura Saikku was responsible of the scenario setting and Sampo Soimakallio conducted the sensitivity analysis.

In **Paper VI**, Tommi Ekholm is the main author. The analysis was jointly planned by Tommi Ekholm, Sampo Soimakallio and Niklas Höhne. Triptych and Multistage calculations were carried out by Sara Moltmann. ETSAP-TIAM calculations were carried out by Tommi Ekholm. The paper was designed and written by Tommi Ekholm, while Sampo Soimakallio, Sara Moltmann, Niklas Höhne, Sanna Syri and Ilkka Savolainen participated in the project and commented on the paper.

Contents

List of symbols and abbreviations

ALCA	Attributional life cycle assessment
BTL	Biomass-to-Liquid
CB	consumption-based
CBA	Cost-benefit analysis
CCS	carbon capture and storage
CEA	Cost-effectiveness analysis
CLCA	Consequential life cycle assessment
CH_4	methane
CHP	combined heat and power production
CO_2	carbon dioxide
CO2-eq.	carbon dioxide equivalent
DFE	design for environment
dLUC	direct land-use change
DM	dry material
DME	dimethylether
EIT	Economies in Transition
EJ	eksajoule (10^{18} joules)
EtOH	ethanol
ETS	Emission Trading Scheme
ETSAP	Energy Technology Systems Analysis Programme
EUROSTAT	the statistical office of the European Union
FAME	fatty acid methyl ester

FT	Fischer-Tropsch
EVOC	Evolution of Commitments
GE	general equilibrium
GDP	gross domestic product
GHG	greenhouse gas
GWP	Global Warming Potential
HVO	hydrotreated vegetable oil
IEA	International Energy Agency
iLUC	indirect land-use change
IMAGE	the Integrated Model to Assess the Global Environment
IOA	input-output analysis
IPCC	the Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LCC	life cycle costing
LCI	life cycle inventory
LCIA	life cycle impact assessment
LHV	lower heating value
LUC	land-use change
LULUCF	Land use, land-use change and forestry
MAC	marginal abatement curve
MCDA	multiple criteria decision analysis
MFA	material flow analysis
MS	Member State (of the European Union)
N_2O	nitrous oxide
non-ETS	all sectors outside the European Union Emission Trading Scheme
OECD	the Organisation for Economic Co-operation and Development
PB	production-based
PE	partial equilibrium
ppm	parts per million
PPP	Purchasing power parity

RED	Renewable Energy Directive
RF	radiative forcing
RME	rapeseed methyl ester
SEEA	Systems for economic and environmental accounts
SETAC	the Society for Environmental Toxicology and Chemistry
SLCA	social life cycle assessment
SRES	Special Reports on Emission Scenarios
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL (market allocation) – EFOM (Energy Flow Optimisation Model) System
UNEP	The United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

1.1 Background

The Earth's environment has been unusually stable for the past 10,000 years (Dansgaard et al. 1993, Petit et al. 1999, Rioual et al. 2001). This stability may now be under threat due to human actions which have become the main driver of global environmental change. This change has been most intensive since the industrial revolution and in particular since the Second World War. Three of nine[1] interlinked planetary boundaries – for a safe operating space for humanity – climate change, rate of biodiversity loss and interference with the nitrogen cycle have already been overstepped (Rockström et al. 2009). In addition, the boundaries for global freshwater use, change in land use, ocean acidification and interference with the global phosphorous cycle may soon be approached. Furthermore, various boundaries are tightly coupled. If one boundary is exceeded, then the others are also under serious risk.

Climate change is the major, primarily environmental issue of our time, and the single greatest challenge facing environmental regulators (UNEP 2012). There is a large scientific consensus that increasing atmospheric concentrations of greenhouse gases have an increasing impact on the global mean surface temperature (IPCC 2007a). The increase in the global temperature may have serious and irreversible impacts on the ecosystems, leading to increasing crisis also for human systems as regards for instance food production, health and safety, and economy. The extent, strength and timing of the implications are not well-known, but are very likely more serious the more the global mean surface temperature increases (IPCC 2007b).

Climate change results from the altered energy balance of the climate system and is driven by changes in the atmospheric concentrations of greenhouse gases (GHGs) and aerosols, changes in land cover and in solar radiation (IPCC 2007a). The positive or negative changes in energy balance due to these factors are ex-

[1] Climate change; rate of biodiversity loss (terrestrial and marine); interference with the nitrogen and phosphorous cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land-use; chemical pollution; atmospheric aerosol loading.

pressed as radiative forcing, which is used to compare warming or cooling influences on global climate (ibid.). Increased atmospheric concentrations of GHGs result in positive radiative forcing tending raise the temperature, whereas anthropogenic contributions to aerosols, surface albedo through land-use changes and depletion of stratospheric ozone produce a cooling effect (ibid.). There is a very high confidence that the global average net effect of human activities since 1750 until 2005 has been one of warming, with a radiative forcing of +1.6 W/m^2 with an uncertainty range from +0.6 to +2.4 W/m^2 (ibid.). Carbon dioxide contributes most significantly to radiative forcing. In 2011 the annual mean atmospheric concentration of carbon dioxide equalled approximately 392 ppm with an annual growth rate of around 2 ppm (NOAA 2012).

Measured as carbon dioxide equivalents based on global warming potential (GWP) over 100 years, the contribution of CO_2 emissions from fossil fuel combustion was approximately 57% of all anthropogenic GHG emissions in 2004 (IPCC 2007c). Similarly, the corresponding contribution of CO_2 emissions from deforestation and decay of biomass was 17%, CO_2 emissions from other sources 3%, methane emissions 14%, N_2O emissions 8% and hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF_6) together 1% (ibid.). Some 26% of the GHG emissions resulted from energy supply, 20% from industry, 17% from forestry, 14% from agriculture, 13% from transport, 8% from residential and commercial buildings and 3% from waste and wastewater (ibid.).

Anthropogenic GHG emissions have increased significantly since pre-industrial times (IPCC 2007c). CO_2 emissions from fossil fuel combustion in particular have increased rapidly during recent decades (Peters et al. 2012). Only economic recessions, namely the oil crisis (1973), the US savings and loan crisis (1979), the collapse of the former Soviet Union (1989), the Asian financial crisis (1997) and the global financial crisis (2008–2009) have temporarily reduced the annual level of these emissions. In 2010, the combined CO_2 emissions from fossil fuel combustion and cement production were the highest ever, equalling 33.4±1.8 Gt CO_2 (Peters et al. 2012). The major emitting countries or country groups in absolute terms were China (26%), USA (17%), EU (12%), India (7%), Russia (5%) and Japan (4%). CO_2 emissions from deforestation and biomass decay have been remarkable in some countries, especially in Indonesia and Brazil in recent decades, thus increasing the contribution of those countries to overall GHG emissions (Houghton 2009).

Countries also contribute to emissions through globalization. The emissions embodied in traded products are becoming increasingly important (Peters et al. 2012, Davis & Caldeira 2010, Peters et al. 2009, Peters & Hertwich 2008). Of the global carbon dioxide emissions in 2008, 26% (7.8 Gt CO_2) were shifted around the globe due to international trade (Peters et al. 2011). Developing countries often produce goods that are used in developed countries. Net fossil CO_2 emission transfers from developing to developed countries increased fourfold between 1990 and 2010.

1.2 Climate policy

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC 1992) is the stabilisation of atmospheric concentrations of GHGs at a level that prevents dangerous anthropogenic interference with the climate system. Furthermore, “such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner”. Article 3.1 of the UNFCCC requires that the mitigation effort should be shared between the parties “on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities”. However, the UNFCCC does not determine any concrete requirements. Thus, among others acceptable limit for global mean surface temperature growth, the emission target levels of various countries and the timing of emission reductions were left open. The Kyoto Protocol (1997) under the UNFCCC obligated industrialised countries to reduce their GHG emissions by 5.2% from the 1990 level on the average between 2008 and 2012. The USA did not ratify the Protocol. The European Union (EU) and later all the countries that have ratified the UNFCCC (1992) have recognized "the scientific view that the increase in global temperature should be below 2°C (EC 1996, 2007, UNFCCC 2010). The Conference of the Parties of the UNFCCC held in Durban in 2011 agreed to reach a new comprehensive climate protocol, another legal instrument or agreed outcome with legal force concerning all the parties (UNFCCC 2011a). However, many details, including the exact form of the agreement and the interpretation of its legal validity as well as emission reduction commitments, remained still open.

According to the IPCC, global GHG emissions should peak no later than 2015 and be reduced by at least 50–85% by 2050 and perhaps even more than 100% prior to the end of the century from their levels in 2000 in order to retain a reasonable probability of limiting the global mean surface temperature increase to under 2°C compared to the pre-industrial level (IPCC 2007c). However, the uncertainties involved in climate modelling are significant. One important but little known parameter is climate sensitivity to increasing atmospheric concentrations of GHGs (IPCC 2007a). In addition, most climate models do not consider long-term reinforcing feedback mechanisms that may further warm the climate, such as decreasing ice cover. Consequently, recently used climate models may underestimate the impacts of increasing atmospheric GHG concentrations (Hansen et al. 2008).

Halting global mean surface temperature increase would require significant improvement in the level of ambition of GHG emission reductions by the parties (UNFCCC 2011a). In order to reach a global solution in climate negotiations, the equity issue has to be solved. Any effort-sharing principle should be politically acceptable with respect to fairness principles and operational requirements (Torvanger & Ringius 2001). The key issue with an effort-sharing method is the dilemma between its transparency, on the one hand, and its ability to take into account national circumstances, on the other (Soimakallio et al. 2006). Each country has to have the impression that it is treated equitably relative to the others in order for it to participate. By the end of 2011, the viewpoints of the major emitters concerning binding emission reduction targets and effort sharing between countries, have been too diverse for a breakthrough in climate negotiations under the UNFCCC.

The EU has unilaterally committed itself to reduce its GHG emissions by at least 20% from the 1990 level by 2020 (EC 2008). Within the EU, GHG emissions are regulated under the two levels: the EU Emission Trading Scheme (ETS) including mainly GHG emissions from energy production and industry (EU 2009a), and at a national level including sectors such as residential, agriculture, transportation and waste management not incorporated in the EU ETS (EU 2009b). As a part of the integrated climate and energy package, the EU also introduced mandatory targets to increase by 2020 the share of renewable energy sources in final energy consumption to 20% and in transportation to 10% (EU 2009c). As a part of this Renewable Energy Directive (RED), mandatory sustainability criteria were introduced for transportation biofuels and other bioliquids, to be accounted for in the targets and allowed to benefit from subsidies. The EU has also set itself a target by 2020 of reducing its primary energy consumption by 20% compared to projections (EC 2011a). In the long term, the EU is committed to reduce GHG emissions by 80–95% by 2050 from their 1990 level in the context of necessary reductions by developed countries as a group (EC 2011b). To achieve its long-term target, the EU has published, among others, roadmaps for resource efficiency (EC 2011c) and energy (EC 2011d).

1.3 GHG emission reduction measures

Ambitious climate change mitigation will require effective climate policy and GHG emission reductions in all countries and all sectors. The emission reduction measures related to energy production and use include improved energy efficiency of the economies, reduced deforestation, fuel switching from coal to gas and from fossil fuels to biofuels (solid, gaseous or liquid), nuclear power, wind power, hydro power, solar and geothermal energy and carbon dioxide capture and storage (CCS). Other options include improved agricultural practices, afforestation, reforestation, forest management, harvested wood product management, recycling and waste and wastewater management. The cost effectiveness and reduction potential of different emission reduction measures vary significantly across countries and sectors. According to van Vuuren et al. (2009), the largest reduction potential as a response to carbon prices exists in the energy supply sector, whereas emission reductions in the building sector may carry relatively low costs. According to IEA (2010a), improvement of end-use fuel and electricity efficiency provides the greatest potential for a substantial reduction in energy-related CO_2 emissions. According to IPCC (2007c), most of the least cost potential for technical emission reduction measures in 2030 exists in non-OECD/EIT countries and in buildings, agriculture, forestry and energy supply.

The uncertainties related to actual GHG emissions in addition to technical, economic and ecological issues, as well as externalities and the development of costs result in uncertainty in the cost-efficiency and potential of use of various emission reduction measures. For example, the forecasted long-term overall availability of bioenergy varies significantly between studies, from some 40–80 EJ/a to over 1,000 EJ/a in the most pessimistic and optimistic scenarios respectively (Bringezu et al. 2009). Expert review of the IPCC (2011) concluded that the potential could be in the range of 100 to 300 EJ/a by 2050. A number of recent studies have concluded that the increased production of biofuels may cause significant environmental and social problems, and that GHG emission reductions achieved by substituting fossil fuels with biofuels, especially liquid biofuels, are unclear due to the auxiliary material and energy inputs required, the direct land-use impact and, in particular, indirect impacts such as deforestation (Searchinger et al. 2008, Fargione et al. 2008, Righelato & Spraclen 2007, Plevin et al. 2010, Runge et al. 2007, Reijnders & Huijbregts 2008, Mitchell 2008, Doornbosch & Steenblik 2007, de Santi et al. 2008, Edwards et al. 2010, Soimakallio et al. 2009). Uncertainty about the interaction of the energy sector with the rest of the economy in its turn increases the uncertainty related to the introduction of various emission reduction measures (Weyant 2000).

1.4 Aims of the study

The fundamental aim of this study is to explore the significance of the uncertainties related to GHG emission reduction measures and policies. Regarding emission reduction measures, the GHG balances of using biomass as transportation biofuels and in heat and electricity production in Finland are studied. Furthermore, the suitability of the European Union sustainability criteria for ensuring GHG emission reductions by increasing the use of transportation biofuels is analysed. In addition, the determination of GHG emissions related to grid electricity consumption at product or process level is studied in general and on average annual basis in OECD countries in particular. Regarding emission reduction policies, effort sharing in ambitious global climate change mitigation scenarios up to 2050 and in the EU by 2020 is studied. The importance of methodological choices and parameter assumptions on the results as well as equity issues are analysed and discussed. Finally, suggestions are given for the way forward.

2. Theoretical framework

The interactions between human activities and the environment can be systematically analysed through industrial ecology (Socolow et al. 1994). The fundamental aims of industrial ecology are to close the loop of materials and substances, and to reduce resource consumption as well as environmental impacts. It is a descriptive discipline, and furthermore a normative discipline, as many industrial ecologists are concerned about the potential environmental impacts of production and consumption, and trying to ascertain how things ought to be, and finding ways to achieve the goals (Lifset & Graedel 2002). Industrial ecology overlaps with many other research fields such as engineering, ecological economics and environmental management. It is neither purely scientific nor purely technological, but includes elements of both.

In industrial ecology several tools from product level to global analysis are utilised. The family of material flow analysis (MFA) are basic analytical tools for industrial ecology derived from the first law of thermodynamics: energy cannot be created or lost (den Hond 2000, Bringezu et al. 1997). At the product or process level, life-cycle assessment (LCA) extends to these analyses by attempting to quantify the environmental impacts of the use of materials and substances, in particular product or process systems (Rebitzer et al. 2004). The resulting environmental profile of a product or process can be used for comparison with competing products or processes or for proposing ways to enhance the particular product or process design through design for environment (DFE) (den Hond 2000). At the global or regional levels, the IPAT concept[2] to study dematerialisation and the effects of technology as well as changes in population and affluence on changes in the environment is used in industrial ecology (Chertow 2000). Furthermore, systems for economic and environmental accounts (SEEA) are established and developed within many countries to be applied at regional or national level (Finnveden & Moberg 2005). In SEEA, environmental input-output analysis (IOA) is used for assessing environmental impacts from different sectors (Finnveden & Moberg 2005). Different types of policy models such as general equilibrium (GE) and partial equilibrium (PE) models are also widely used to provide scenario data at global or regional level.

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[2] Environmental impact (I) = Population (P) x Affluence (A) x Technology (T).

3. Material and methods

3.1 Methodological framework

3.1.1 Product level analysis

Life Cycle Assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts related to the life cycle of a product system (product, process or service) (ISO 2006:14040, 2006:14044). Two main categories of LCA have been defined: attributional and consequential (Finnveden et al. 2009, Curran et al. 2005). The Attributional LCA (ALCA) has been defined as a method "to describe the environmentally relevant physical flows of a past, current, or potential future product system". In contrast, the Consequential LCA (CLCA) can be defined as a method that aims to describe how environmentally relevant physical flows would have been or would be changed in response to possible decisions that would have been or would be made. The ALCA reflects the system as it is, whereas the CLCA attempts to respond to the question: "What if?". The Attributional LCA excludes the use of marginal data. Instead, some sort of average data reflecting the actual physical flows is used (Finnveden et al. 2009). In contrast, in Consequential LCA marginal data is used when relevant for the purpose of assessing the consequences (Ekvall and Weidema 2004).

The LCA is initiated by defining the goal and scope; this is followed by a life cycle inventory (LCI), a life cycle impact assessment (LCIA) and an interpretation of the results (ISO 2006:14040). Definition of the appropriate system boundary and other methodological choices, for example allocation methods and functional unit, depend on the goal and scope of the study. Reflecting the iterative nature of LCA, decisions regarding the data to be included should be based on a sensitivity analysis to determine their significance (ISO 2006:14044). Allocation is one of the major unsolved issues in LCA. According to ISO standards, it should be avoided whenever possible by dividing the unit process to be allocated into two or more sub-processes or by expanding the product system to include all the additional functions related to co-products. If allocation cannot be avoided, it should reflect the underlying physical relationships between products or functions or be based on other relationship. (ISO 2006:14044.)

Uncertainty is involved in every step of LCA from the goal and scope definition to interpretation. According to Huijbregts (2001), the uncertainty in LCA is due to 1) methodological choices such as spatial and temporal system boundary, functional unit and allocation procedure, 2) parameters such as inaccurate or outdated measurements or lack of data, and 3) models such as loss of spatial and temporal dimension when accounting for emissions and derivation and application of characterization factors. In addition, variation in the results is due to spatial and temporal variability and variability in objects and sources. The ISO 14040 and 14044 does not give concrete guidance on how the uncertainties should be analysed. According to Finnveden et al. 2009, uncertainty can be handled in several ways. The "scientific" way to deal with large uncertainties is to do more research to lower the uncertainty; the "social" way is to discuss the uncertain issues with stakeholders and to find a consensus. The "statistical" way does not try to remove or reduce the uncertainty, but intends to incorporate it. For the latter option, a number of methods are available, including parameter variation and scenario analysis, classical statistical theory on the basis of probability distributions, tests of hypothesis, Monte Carlo simulations and other sampling approaches, analytical methods based on first-order error propagation, non-parametric analysis, Bayesian analysis, Fuzzy set theory and qualitative uncertainty methods (Finnveden et al. 2009).

In this study LCA is applied to assess GHG emissions of transportation biofuels and biomass-based power and heat production in Finland by considering the reference fuels to be substituted (Paper I). Transportation biofuel technologies for which GHG emissions were not previously studied in Finland were selected for consideration. Critical issues resulting in uncertainty of the LCA are considered in the "statistical" way. The significance of parameter uncertainty is reflected for the technologies considered. Previously, only a few LCA studies have conducted parameter uncertainty analysis by using stochastic simulation (Williams et al. 2009, Lloyd & Ries 2007).

The importance of setting a system boundary and selecting allocation methods is studied for determining CO_2 emissions from annual average electricity consumption in OECD countries (Paper IV). Previous studies have examined the GHG emissions of single electricity production technologies (Weisser 2007), the impact of allocation method on CO_2 emissions from CHP (e.g. Graus & Worrel 2011, Frischknecht 2000) and the uncertainty of CO_2 emission intensities at various geographic levels in the continental US (Weber et al. 2010). Also, the role of international trade on GHG emissions in general has been studied (e.g. Peters & Hertwich 2008). However, the above-mentioned issues have not been studied comprehensively and transparently together to a wider extent for a range of countries.

Furthermore, the significance and suitability of selection between the ALCA and CLCA approach, the setting of spatial and temporal system boundary, the selection of allocation methods and sources of parameter uncertainty are critically discussed in the context of grid electricity consumption in general (Paper III) and in the context of the sustainability criteria for transportation biofuels and other bioliquids introduced as a part of Renewable Energy Directive (RED) of the EU (Paper II). Regarding electricity consumption, only a few studies overall have been published previously on the methodological issues and data uncertainties, and a comprehensive picture was lacking. In addition, the suitability of the mandatory sustainability criteria to ensure the GHG emission reductions by increasing the use of transportation biofuels and other bioliquids was analysed and discussed critically for the first time in Paper II.

3.1.2 Global and regional level analysis

Macro-level scenarios describing the relations between the economy, the energy sector and the environment can be carried out by using two different modelling approaches called top-down and bottom-up (IPCC 2007c). Top-down modelling describes the macro-economic relations in the region under consideration, thus evaluating the system through aggregate economic variables. Top-down models may apply rather simple descriptions of, for example, country-level future development of energy consumption by primary energy sources and economic sectors. On the contrary, bottom-up modelling includes detailed descriptions of all the processes involved. In order in bottom-up models to construct a scenario, the development of all the parameters needs to be specified, and the impacts of individual factors or interlinkages of various factors are considered.

In this study, effort sharing of emission reduction commitments between countries and country-groups are analysed by applying both top-down and bottom-up modelling. The uncertainty is propagated in the “statistical” way. A few top-down approaches based on macro-economic figures are studied for sharing the national emission reduction targets between the EU Member States by 2020 (Paper V). The effort sharing at a global level up to 2050 was studied based on two top-down approaches, namely Triptych and Multistage (Höhne et al. 2006) and analysed by using the bottom-up partial equilibrium energy system model ETSAP-TIAM (Loulou & Labriet 2008, Loulou 2008, Syri et al. 2008, Koljonen et al. 2009) under different socio-economic baseline scenarios (Paper VI). ETSAP-TIAM model has not previously been used to analyse the emission reduction and cost implications of effort sharing. Cost-effectiveness analysis (CEA)[3] was applied as a methodology to characterize the cost implications.

3.2 System description and data

Six different papers are included in this study (Table 1). In four of the papers (I–IV) LCA is applied as a methodological framework, of which two are related to GHG

[3] CEA is a form of economic analysis and a special case of cost-benefit analysis (CBA) in which all the costs of a portfolio of projects (e.g. GHG emission reduction costs) are assessed in relation to a policy goal such as a GHG emission reduction target (Sathaye et al. 1993). CBA is a systematic process to measure all the negative and positive impacts and resource uses of a project, decision or government policy in the form of monetary costs and benefits (Squire & van der Tak 1975, Ray 1984).

emissions of biofuels (I, II) and two concerning GHG emissions of grid electricity consumption (III, IV). Top-down modelling is applied in Paper V, and both top-down and bottom-up modelling are applied in Paper VI to consider GHG emission reduction effort sharing in the context of climate policy. One of the six Papers (IV) is retrospective in nature and concerns only CO_2 emissions, whereas the others are future-oriented covering all the relevant GHG emissions. In characterizing GHG emissions, two of the Papers (I, V) clearly rely on Global Warming Potentials calculated by using 100-year time frame (GWP-100). In Paper VI both Radiative Forcing (RF) and GWP-100 factors are applied. Sections 3.2.1–3.2.6 below provide an overview of the system considered and the major data sources used in each of the papers. More detailed description is provided in the respective papers.

Table 1. Illustrative description of the scope and type of the papers.

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**	**Paper VI**
Characterization	Data-oriented	Discussion	Discussion	Data-oriented	Data-oriented	Data-oriented
Technology/ sector	Biomass-based transportation fuels, electricity, heat	Transportation biofuels and other bioliquids	Electricity	Electricity	Non-ETS sector	All sectors excl. LULUCF
Region	Finland	EU-27	not specified	OECD	EU-27 MSs	Global in 15 regions
Time	Future-oriented, not specified	2020	Future-oriented, not specified	1990–2008	2020	2020, 2050
Emission components	GHGs	GHGs	GHGs	CO_2	GHGs	GHGs
Emission characterization	GWP-100 (IPCC 1996)	GWP-100 (IPCC 2001) / not specified	Not specified	Not considered	GWP-100 (IPCC 1996)	GWP-100 (IPCC 1996) / RF
Methodological framework	CLCA	ALCA/CLCA	ALCA/CLCA	ALCA	Sectoral top-down	Sectoral top-down / bottom-up, CEA
Main type of uncertainty considered	Parameter	Methodological choices, Parameter, model	Methodological choices	Methodological choices	Methodological choices, Parameter	Methodological choices, Parameter
Methods for uncertainty propagation	Stochastic modelling	Not considered	Not considered	Parameter and system boundary variation	Parameter variation and scenario analysis	Parameter variation and scenario analysis

3.2.1 GHG balances of biofuels in Finland (Paper I)

In this paper, GHG emission reductions of biomass used as transportation fuels, and in heat and electricity production in Finland when replacing reference fuels are assessed. Principles of the CLCA approach were followed. Allocation was avoided through system expansion. One kilometre driven and one kilowatt hour produced were selected as functional units for transportation fuels and electricity/heat production respectively. Parameter uncertainty analysis was conducted by using Monte Carlo simulation with 15,000 samples. Calculations were carried out using MS Excel software (vs 2003) and its add-in software Crystal Ball (vs 2000). The transportation biofuel technologies considered include ethanol from barley, rape methyl ester (RME) diesel from (spring) turnip rape, Fischer Tropsch (FT) diesel from logging residues and reed canary grass.

For FT diesel production, three different process concepts were assumed, including stand alone process and processes integrated into a pulp and paper mill which minimizes either electricity or biomass consumption. In addition, electricity and/or heat production from logging residues and reed canary grass were considered. Fossil diesel was considered as a reference fuel for RME and FT diesel, and gasoline was considered as a reference fuel for ethanol. Marginal electricity with its assumed minimum and maximum values was considered to provide boundaries for calculating the credits of replacing electricity and/or heat production by biofuels.

It was assumed that no commercial reference use for the raw materials takes place. Agrobiomass-based raw materials were assumed to be cultivated on set-aside lands, whereas logging residues were assumed to be left in the terrain in the reference situation. Protein animal meal generated in the ethanol and RME biodiesel process was assumed to replace the use of soy protein imported from the USA. Glycerine produced in RME process was assumed to be used for energy in heat production boilers to replace peat. Straw was not assumed to be harvested.

Unit processes considered include auxiliary energy inputs (crude oil, diesel oil, electricity), auxiliary chemical inputs (fertilizers, limestone, pesticides, sulphuric and phosphoric acid, smectite, caustic soda and hexane) and soil processes (N_2O emissions from fertilization, CO_2 emissions from limestone and changes in soil carbon balances). The construction of infrastructure, the production of facilities, machinery and other equipment required in overall fuel production chains were excluded from both bioenergy and reference fuel chains.

Data on cultivation, harvesting, transportation and crushing of biomass raw materials was based on Mäkinen et al. 2006. Intensities for direct and indirect N_2O emissions from soils due to fertilization were derived from IPCC (2006) and Statistics Finland (2006). Data on compensation fertilization of forest lands and soil carbon losses due to logging residue harvesting was based on Wihersaari (2005). Data on soil carbon changes due to agricultural land management was taken from IPCC (2006). Data on biofuel processing chemicals and energy balance of RME diesel processing was taken from Elsayed et al. (2003). Data on processing of the other fuels and combustion of the fuels was based on Mäkinen et al. 2006. Data on the supply of diesel oil, heavy fuel oil and natural gas required in machinery and equipment, pesticides and substitution credits of soybean meal was based on Edwards et al. (2003). CH_4 and N_2O emissions from fuel combustion in machinery and boilers and specific fuel consumption and the GHG emissions of transport were derived from Statistics Finland (2006) and LIPASTO calculation system of VTT (2006). Data on substitution credits from peat combustion was derived from Kirkinen et al. (2007).

All variables were presented with a three-parameter Weibull distribution and determined as uncorrelated. An exception to this was GHG emissions from electricity consumption and substitution, for which a uniform distribution was assigned. The uncertainty range given for each variable was based on the data sources used and expert evaluation.

3.2.2 EU sustainability criteria analysis (Paper II)

According to the sustainability criteria introduced in the Renewable Energy Directive (RED) of the EU, the GHG emission reductions compared to fossil comparator should be at least 35% for biofuels and other bioliquids produced before the end of 2016. From the beginning of 2017, the GHG emission reductions should be at least 50% and from the beginning of 2018, the GHG emission saving should be at least 60% for biofuel production installations where production begins after 1 January 2017.

The RED provides the default values for GHG emission reductions (%) of a range of biofuels compared to fossil reference fuels. These default values can be used if GHG emissions from land-use changes can be proved to be equal to or less than zero. In addition, the RED provides disaggregated default values, separately and as aggregate, for cultivation, fuel processing and transport and distribution for a range of biofuels expressed as g CO_2-eq./MJ_{fuel}. Disaggregated default values for cultivation can only be used if the raw materials are cultivated outside the European Community, are cultivated in the Community areas included in the specific list referred to in the RED, or are waste or residues from other than agriculture, aquaculture and fisheries. If the above mentioned conditions are not fulfilled, if the default value for the GHG emission saving from a specific production pathway falls below the required minimum level or if the default value does not exist, biofuel producers are required to use the RED methodology to show that the actual GHG emission reductions resulting from their production process fulfil the set criteria. Furthermore, the biofuel producer may always use the actual value instead of the default value.

The GHG emission reduction is defined as the relative reduction compared to reference fuel by the Equation:

$$\text{EMISSION SAVING} = (EF - EB) / EF \quad (1)$$

where,

E_B = total emissions from the biofuel or other bioliquid; and

E_F = total emissions from the fossil fuel comparator.

Equation 1 takes into account the GHG emissions from the different phases from cultivation (crops) or collection (waste and residues) of raw materials to the use of biofuel. GHG emissions from the production of machinery and infrastructure are excluded. Allocation should be based on lower heating value of the products in the case of co-products other than electricity. The other details of the formula are given in the part C of Annex V of the RED. For the implementation of the RED into national legislation of the EU Member States, the European Commission issued two Communications. These include practical guidelines on the implementation of the sustainability system and the associated calculation rules (EC 2010a), and a Communication on voluntary certification systems and default values (EC 2010b). In addition, a Decision on the calculation of land carbon stocks in the case of land-use changes was issued (EC 2010c).

In Paper II, the conservativeness of the default values provided in the RED for GHG emission reductions (%) compared to fossil reference fuels for a range of biofuels was analysed by comparing them to figures presented in the literature. In addition, the methodology introduced in the RED to calculate actual GHG emission reductions was analysed considering the most critical issues, problems and challenges that are encountered when assessing life cycle GHG emissions of transportation biofuels and other bioliquids in general.

3.2.3 Determination of GHG emissions of electricity consumption (Paper III)

Electricity cannot be stored as such, and is therefore consumed virtually at the same time as it is produced. Electricity can, however, be transmitted over even long distances via overhead lines and power cables. Within an electrical network, the consumption and thus also the production typically varies between times of day, seasons and years. Furthermore, the electricity production mix varies from one moment to another, and can be very different in different electrical grids. These specific properties make the assessment of GHG emissions associated with the individual process of consuming or conserving grid electricity a complex and challenging procedure. However, the particular information is highly relevant and required for almost any environmental impact assessment in one form or another.

In Paper III, a methodological review of the complexity and challenges of determining GHG emissions from individual processes that consume or conserve grid electricity was carried out by means of a literature survey. The critical issues and uncertainties involved were discussed. The viewpoints of ALCA and CLCA approaches were reflected.

3.2.4 CO_2 emission intensity of electricity in OECD countries (Paper IV)

In Paper IV, the CO_2 emission intensity of annual average electricity consumption in the 30 OECD countries was examined in 1990, 1995 and 2000–2008 by both ignoring and considering the CO_2 emissions embodied in the electricity trade. First, the annual production-based CO_2 emission intensity of electricity (g CO_2/kWh) was calculated by determining the total CO_2 emissions from fuel combustion in power production and dividing this by the total amount of electricity produced and transferred to consumption points within a country. In the production-based approach, it was assumed that electricity imports to a country have the same CO_2 emission intensity as the electricity produced within the particular country.

Second, the CO_2 emissions embodied in the electricity trade were calculated and the consumption-based CO_2 emission intensity of electricity (g CO_2/kWh) was estimated. In the case where an OECD country imports electricity from a non-OECD country, the production-based CO_2 emission intensity of electricity supply for the non-OECD country in question was calculated. In cases where the origin of electricity import was not known or no reliable data was available (electricity imports from Luxembourg to Germany between 1990 and 2000), the production-based CO_2 emission intensity of the OECD average was applied.

Two different methods were selected for allocation of CO_2 emissions from combined heat and power production (CHP) to heat and power. For the lower limit of CO_2 emissions attributed to electricity, emissions were allocated on an equal basis to electricity and heat output in enthalpic terms. For the upper limit of power-related CO_2 emissions from CHP, the 'motivation electricity' method was selected, allocating 100% of the emissions to electricity.

The latest available data from the International Energy Agency (IEA) was used. The CO_2 emissions from fuel combustion, categorised as electricity output from the main electricity producers, autoproducers and combined heat and power producers, as well as own use of electricity, were taken from the IEA database 'CO_2 emissions from fuel combustion' (IEA 2010b). The data for electricity production, distribution and transformation losses, imports, exports and final consumption, as well as electricity and heat production in CHP plants was taken from the IEA database 'Energy Balances' (IEA 2010c). The data for bilateral electricity trade of the OECD countries was taken from the IEA publication 'Electricity Information' (IEA 2010d). The overall national CO_2 emission data was taken from the UNFCCC (2011b).

3.2.5 Effort sharing in the EU by 2020 (Paper V)

In Paper V, top-down macro-level figures were used to set the emission reduction targets for the 27 Member States of the EU. Four effort-sharing criteria were generated for emission reduction in sectors outside the Emission Trading Scheme (ETS) referred as non-ETS. In Scenario 1, the annual rate of change in GHG/GDP was assumed to be the same in all Member States over the 13 years 2008–2020. In Scenario 2 it was assumed that GHG/GDP converges for all countries by 2020. In Scenario 3 it was assumed that national annual rates of GHG/GDP development are the same as they were in 1993–2005. In order to reach a reduction of 20% by 2020, an additional reduction was required. This additional annual reduction was set as a constant over time and the same for all countries in percentage terms. In Scenario 4 it was assumed that per capita GHG emissions converge for all countries by 2020. The reduction in the non-ETS sector was determined through reductions in the ETS sector. In the ETS sector, each country was hypothetically set to reduce its emissions by the same proportion compared to their verified ETS sector emissions in 2005. The first year when emission reduction requirements were assumed to take place was 2008.

A few test runs were conducted for all scenarios to analyze certain sensitivities involved in the results. In the test runs, the base year (starting point for reductions) for emissions and GDP was changed. In addition, the period for ETS reductions was changed from the latest verified emissions to allocated future emissions. In addition, ETS reductions as a proportion of the total reduction were changed. Moreover, GDP and population forecasts were varied.

The historical data for GHG emissions and GDP, as well as forecasts for population growth in the different EU Member States was derived from the Eurostat database (Eurostat 2008). Forecasts of economic development were carried out according to a model described in Saikku et al. (2008). GDP estimates for the non-ETS sectors were used in the calculation. The approximated GDP share of the sectors included in the ETS was based on Eurostat (2008) GDP data. Required GHG emission intensities were compared to recent historical development in the scenarios. Historical developments in GHG/GDP during 1993–2005 were calculated for total GDP. Non-ETS GHG estimates for 1993 were based on Eurostat (2008). GDP data for 1993 were taken from the Penn World Table (Heston et al. 2007).

3.2.6 Global effort sharing up to 2050 (Paper VI)

Paper VI focuses on the equity of effort sharing with two exogenously assumed reduction targets that would stabilize greenhouse gas atmospheric concentrations to 485 ppm CO_2-eq. and 550 ppm CO_2-eq. by year 2100. The corresponding GHG emission developments from 1990 were +20% (by 2020) and -50% (by 2050) and +30% (2020) and -10% (2050), respectively. The emission level of 2050 was assumed to be constant for the period between 2050 and 2100. Based on assumptions on global emission paths, the resulting atmospheric GHG concentrations, radiative forcing and global mean surface temperature increase (using 3°C climate sensitivity) up to 2100 were calculated.

A relatively simple and transparent tool, Evolution of Commitments (EVOC), was used to calculate the effort sharing based on Triptych and Multistage approaches (Höhne et al. 2006). Such allocations of emissions were then analysed in long-term energy-climate scenarios produced with ETSAP-TIAM (Loulou & Labriet 2008, Loulou 2008, Syri et al. 2008, Koljonen et al. 2009), a more sophisticated integrated assessment model.

The EVOC tool contains collections of data on emissions from several sources, and future projections of relevant variables from the Integrated Model to Assess the Global Environment (IMAGE) implementation of the IPCC SRES scenarios marked as A1, A2, B1 and B2. As emission data varies in its completeness and sectoral split, EVOC combines data from the selected sources and harmonizes it with respect to the sectoral split. Future emissions are based on IMAGE projections of parameters, such as population, GDP (PPP), electricity consumption and industrial value added. As IMAGE projections are available only for 17 world regions, EVOC deaggregates this data by combining it with historical values. Finally, the user can set the parameters of several effort sharing rules in order to calculate emission allocations.

In the Triptych approach (Phylipsen et al. 1998, Groenenberg et al. 2001, den Elzen et al. 2008a) the emission target for each sector is calculated with given assumptions on the reduction potentials in the sector. The Triptych version 6.0 that was used in the study is documented by Phylipsen et al. (2004). This version uses six sectors: Electricity, Industry, Fossil fuel production, Domestic, Agriculture and Waste. The electricity and industry sectors use parameters on efficiency, structure and income levels to calculate the emission limits. Domestic and waste sectors use a single convergence level, given in terms of t CO_2-eq./capita, to which the emissions of countries converge by a given year. For fossil fuel production and agriculture, reduction levels from the baseline are assumed. In addition to this sectoral differentiation, Triptych also uses a rough income categorization with some parameters to distinguish countries with different levels of affluence. The emission allocation of a country is then the sum of the sectoral targets.

In the Multistage approach the countries participate in several stages with differentiated levels of commitment (den Elzen et al. 2006). Each stage has stage-specific commitments with countries graduating to higher stages when they exceed certain thresholds, and all countries agree to have commitments at a later point in time. For this study, thresholds and commitments were applied based on per capita emissions with four stages. The cap-and-trade system was assumed to bind all countries so that the countries without binding commitments receive emission allocations according to their baseline emissions, but are then free to mitigate emissions and sell the excess allowances for profit.

The energy and emission scenarios in this paper were devised using the ETSAP-TIAM (TIMES Integrated Assessment Model) which is based on the TIMES (The Integrated MARKAL-EFOM System) modelling methodology (Loulou et al. 2005). The TIMES family of models are bottom-up type linear partial equilibrium models that calculate the market equilibrium through the maximization of the total discounted economic surplus with given external end-use demand projections. The ETSAP-TIAM models the whole global energy system with 15 geographical regions. Main assumptions concerning the energy system, future energy technologies, potentials, other emission reduction options and climate module in the model are described in Syri et al. (2008). All GHGs regulated under the Kyoto Protocol were considered from all anthropogenic sources, except emissions from land-use changes.

The geographical region split of the ETSAP-TIAM model was used. The externally given energy consumption in the ETSAP-TIAM model, based on the growth of regional GDP, was harmonised to fit with the four IPCC SRES scenarios considered. The GHG emission reduction costs considered include direct costs, changes in energy trade, GHG emission allowance trade and the value of lost demand due to price elasticity. Indirect macroeconomic costs, damage costs and possible benefits from avoided climate change, relevant in cost-benefit analysis (CBA), were ignored.

4. Results

4.1 Biofuels

GHG emissions from the production and use of ethanol derived from barley and RME diesel derived from turnip rape in Finland were very likely (with 94% and 98% probability, respectively) higher compared to the fossil reference fuels (Figure 1). The wide uncertainty range and high upper limit (Figure 1) resulted mainly from a significant uncertainty in N_2O emissions from soils due to fertilisation (Table 2). Other dominant factors affecting uncertainty were yield per hectare, animal feed output and emissions from electricity production. GHG emissions from producing FT diesel were lower compared to fossil diesel, but the value depended significantly on the concept considered. If the biomass requirement was minimised, GHG emissions of FT diesel were highly dependent on emissions from production of electricity consumed in the process. If the purchased electricity requirement was minimised and replaced by more biomass, the uncertainty range was decreased significantly, and soil carbon losses due to logging residue harvesting became the most dominant factor. The probability distributions for GHG emission reductions of biofuels derived from logging residues and reed canary grass were very similar compared to each other.

The GHG emission reduction in replacing electricity and/or heat by bioenergy was highly dependent on the emission factor given for the replaced energy (referred to as emission savings from replaced electricity in Table 2). The emission factor given for electricity has the opposite impact on the results in the case of replacing marginal electricity compared to consuming electricity in the case of transportation biofuels. Consequently, the higher emission factor of electricity increases the emission reduction achievable by using logging residues or reed canary grass in electricity production and decreases the emission reduction achievable by using the particular raw materials as transportation biofuels.

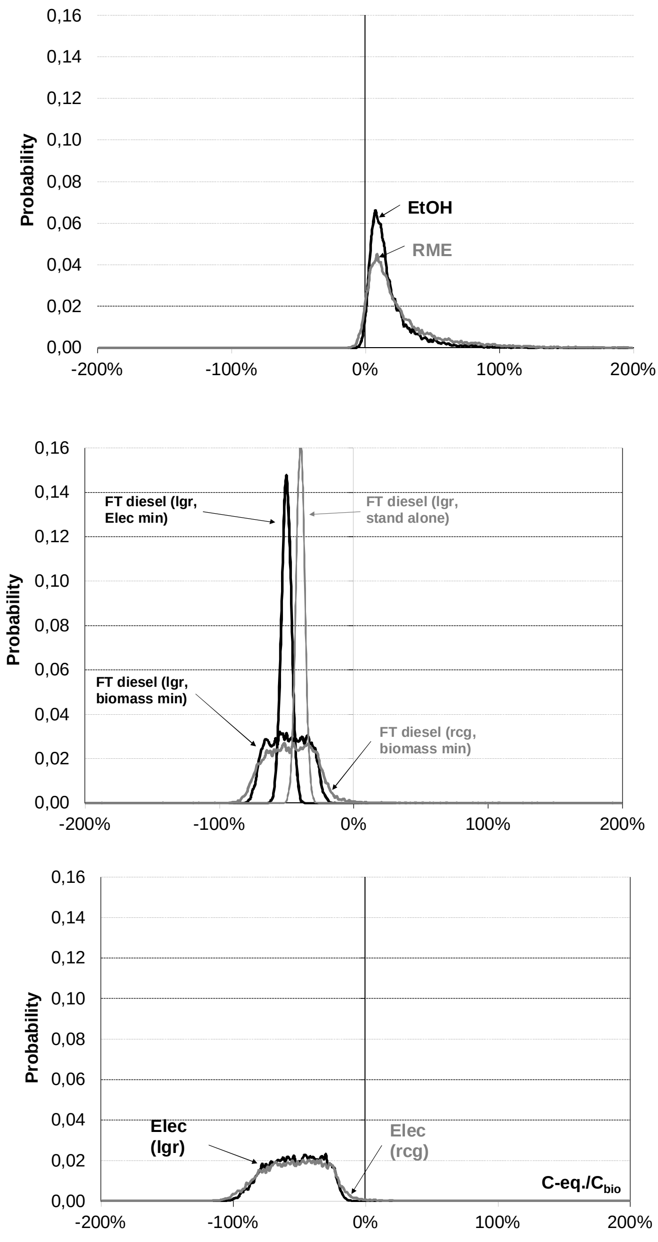

Figure 1. Probability distributions for carbon equivalent emission impact per consumed biocarbon when replacing reference fuels (Paper I). Positive values refer to emission increase. (Elec = electricity production, lgr = logging residues, rcg = reed canary grass, elec min and biomass min refer to integrated FT diesel processing cases with minimum purchased electricity and biomass, respectively.)

Table 2. Mean value, 95% central confidence interval and Spearman's rank correlation between 10 most important uncertainty variables and the GHG emission reduction per biocarbon consumed for biofuel chains studied in Paper I. (Elec = electricity production, lgr = logging residues, rcg = reed canary grass, elec min and biomass min refer to integrated FT diesel processing cases with minimum purchased electricity and biomass, respectively.) (Adapted from Paper I.)

Statistical measure	**EtOH**	**RME**	**FT (lgr, biomass min)**	**FT (lgr, elec min)**	**FT (lgr, stand alone)**	**FT (rcg, biomass min)**	**Elec (lgr)**	**Elec (rcg)**
2.5%:ile value (%)	-1%	-3%	-74%	-58%	-47%	-79%	-93%	-98%
Mean value (%)	17%	25%	-49%	-50%	-40%	-47%	-53%	-53%
97.5:ile value (%)	65%	106%	-26%	-45%	-34%	-15%	-22%	-14%
Spearman's rank correlation parameters								
Emission from electricity production	0.27	0.07	**0.97**	0.36	0.09	**0.89**		
Electricity demand			0.06	0.02	0.01	0.04		
Yield rate of raw material	-0.26	-0.27				-0.16		-0.13
Carbon content in DM of raw material	-0.07					0.15	-0.01	0.12
LHV in DM of raw material			-0.04	-0.18	-0.15	-0.04	-0.04	-0.03
N_2O from soil (fertilization)	**0.84**	**0.88**	0.04	0.14	0.01	0.25	0.03	0.20
Fertiliser use	0.12	0.09				0.03		0.02
Emissions from fertiliser production	0.10	0.11						0.02
Ploughing								-0.02
Animal feed output		0.15						
Soil carbon losses	0.16	0.14	0.21	**0.84**	**0.94**		0.13	
Emission savings from replaced electricity							**-0.95**	**-0.89**
Efficiency of biofuelled power plant							-0.27	-0.26
Emissions of biofuelled power plant							0.02	
Output of produced fuel		-0.15	-0.05	-0.21	-0.19	-0.03		
Emission savings from replaced soybean meal	-0.06	-0.06						
Emissions from replaced reference fuel	-0.05		-0.06	-0.17	-0.15	-0.05		
Emissions from transportation			0.02	0.06	0.08	0.03	0.02	0.03
Emissions from forest haulage			0.01	0.02	0.02		0.01	
Emissions from chipping			0.01	0.01	0.02		-0.01	
CO_2 from liming	0.05							
lime use		0.06						

The conservativeness of the GHG emission default values provided in the sustainability criteria of the EU Renewable Energy Directive (RED) was analysed in Paper II. Based on the literature survey, the GHG balance figures for various biofuel supply chains vary significantly around the default values provided in the RED (Figure 2). Some very high GHG emission estimates were found from the literature for biodiesel derived from palm oil and soya oil, and ethanol derived from grains. Such figures include CO_2 emissions from converting permanent forests to arable lands, directly or indirectly. Also, lower GHG emission estimates were found compared to the default values of the RED. The variation in the results for specific raw materials may be due to differences in spatial system boundary setting, handling of timing issues, allocation procedure and parameter assumptions. The 95% central confidence interval figures presented in Paper I for the relative GHG emission impact are also presented as GHG emissions of relevant biofuels[4] in Figure 2. Those figures fall in the range, with the exception that the upper limit for FT diesel from logging residues (BTL wood residues in Figure 2) was higher than any other figures found in the literature considered. On the other hand, not many figures were available for BTL from wood residues.

[4] The conversion from relative GHG emission impact has been carried out in accordance with the methodology explained in the supplementary material of Paper II (by using a GHG emission factor of 83.8 g CO_2-eq./MJ for fossil fuel replaced)

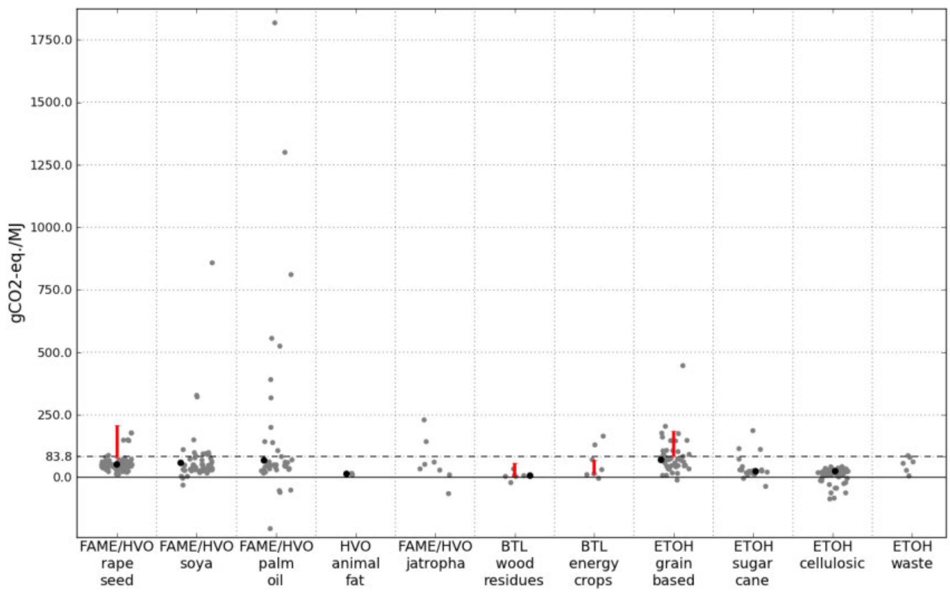

Figure 2. GHG balances of different biofuels produced from various raw materials in different regions and using different process technologies (adapted from Paper II). The black dotted line illustrates the GHG balance of the fossil reference fuel (gasoline and diesel) including CO_2 emission from fossil fuel combustion in accordance with the RED. The default values of the RED for certain raw materials and technologies are illustrated by black circles. In case the RED provides more than one default value for a certain technology route, the maximum value is presented. The vertical bars (red coloured) illustrate the range between the 95% central confidence interval of GHG emissions of biofuels studied in Paper I.

4.2 Grid electricity consumption

The variation in annual production-based CO_2 emission intensities of electricity in the countries studied in Paper IV was significantly high, ranging from almost zero in Norway during all the years studied to over 1,800 g CO_2/kWh in Poland in 1990 (Tables A1 and A2 in Appendix A). However, high values of over 1,000 g CO_2/kWh occurred only in three countries, namely Poland, the Czech Republic and Greece, during the period studied. In these countries, the use of fossil fuels, in particular coal, constituted a significant proportion of electricity production. The high values may also indicate poor quality of the original data or relatively low conversion efficiency. Apart from Norway, other examples of countries with low production-based CO_2 emission intensities were Sweden and Switzerland. The higher the fossil-fuel-based electricity production was in a given country, the higher was the CO_2 emission intensity of energy production. The share of fossil fuels in the electricity production mix varied significantly between countries (IEA 2010c).

The annual variation in production-based CO_2 emission intensity of electricity was moderate at the average OECD level, but considerable for many individual countries due to changes in the fuel mix and production technologies (Tables A1 and A2 in Appendix A). Examples of such countries are Luxembourg, Norway, Finland, Sweden, Denmark and France. For the Nordic countries, in particular, annual fluctuations in hydropower and nuclear power production significantly affected the respective amount of fuel used in electricity production.

The allocation procedure for CHP increased the variability of the results when the amount of electricity produced with CHP was high (Tables A1 and A2 in Appendix A). Examples of countries with a relatively high share of CHP in electricity production are Poland, Denmark, Finland and Sweden. Relatively, the largest range in estimated production-based CO_2 emission intensity of electricity due to the allocation procedure for CHP was in Sweden, where the lower end (energy-based allocation) CO_2 emissions totalled only 30% of the CO_2 emissions at the higher end (all for electricity) on average between 2000 and 2008. Other countries where the respective ratio due to variation was significant were Switzerland (54%), Denmark (55%), Norway (57%), and Finland (65%).

The difference between national production-based (Tables A1 and A2 in Appendix A) and consumption-based (Tables A3 and A4 in Appendix A) CO_2 emission intensity of electricity was highly significant for Switzerland, Norway, Slovakia, Austria and Sweden, and fairly significant for Denmark, Finland, Hungary and Italy (Figure 3). Of these countries, only Denmark was a net exporter of CO_2 emissions embodied in electricity trade (Figure 2 in Paper IV). For the rest of the countries studied, the difference was typically less than 10% within the years studied. The Netherlands, for example, imports a significant share of its final electricity consumption, but mainly from Germany, in which the CO_2 emission intensity of electricity production is relatively close to that of the Netherlands. For a few European countries with a high share of electricity trade compared to final electricity consumption, the CO_2 emissions embodied in electricity trade were significant compared to overall national CO_2 emissions. Such countries include Switzerland, Slovakia, Luxembourg, Austria and Finland.

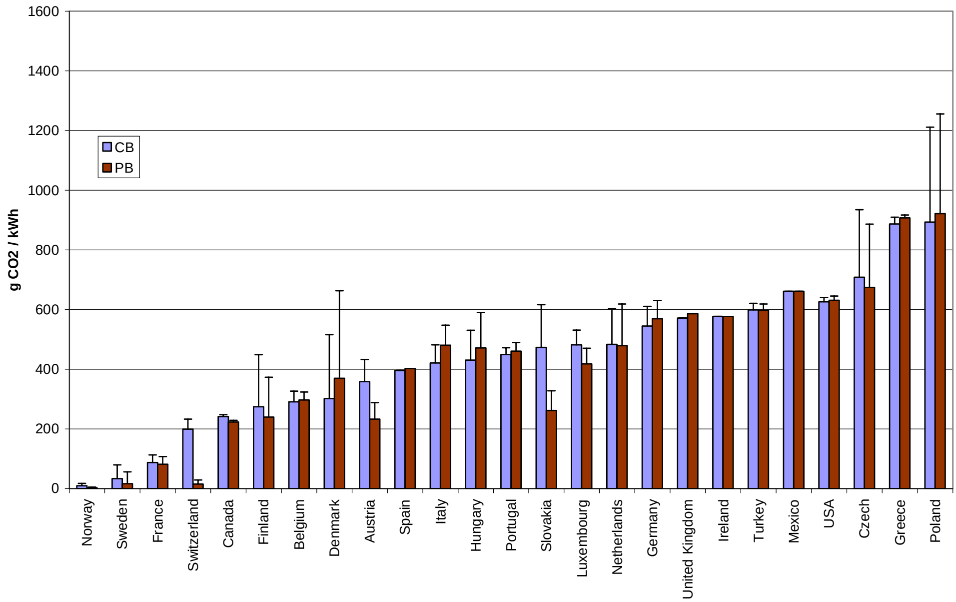

Figure 3. Production-based (PB) and consumption-based (CB) CO_2 emission intensities of electricity (g CO_2/kWh) in OECD countries with electricity trade averaged between 2006 and 2008 (Paper IV). The error bars illustrate the impact of the selected method for the allocation of CO_2 emissions between electricity and heat in combined heat and power production (CHP). The coloured columns correspond to the energy-based allocation and the upper limit of the error bars correspond to the 'motivation electricity' method.

4.3 Differentiation of emission reduction commitments

4.3.1 At the EU level by 2020

The macro-level perspective in sharing national GHG emission reduction commitments between the EU Member States was examined in Paper V with respect to achieving the 20% reduction in 1990 level GHG emissions within the European Union by 2020. Only the sectors outside the EU ETS (i.e. non-ETS), such as transportation, housing, services and agriculture, were considered.

Countries' GHG emission reduction targets were determined by their level of GHG emissions in the starting year (2008), their recent GDP and population level and growth expectations. Also, historical development in GHG/GDP had an impact in one scenario. The overall variation among the Member States in the required GHG emission reduction targets was found to be large, although the variation between scenarios was moderate for a few large EU countries (Figure 4). The required country-specific reductions were dependent on the applied principle of effort sharing, the allocation of reductions between ETS and non-ETS sectors, the selected base year for GDP and emissions, and especially on the economic forecasts used. The national GHG emission target set by the EU (EU 2009b) is out of the studied range for Spain, Lithuania, Italy, Slovenia and Estonia, but close to the average range of the studied scenarios for most of the countries (Figure 4).

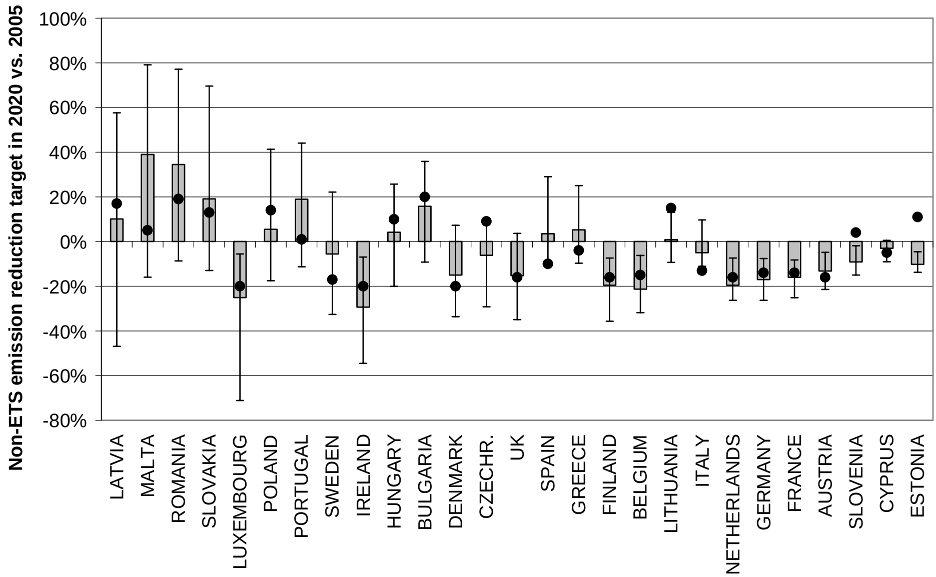

Figure 4. Average change in non-ETS GHG emissions by 2020 in comparison with 2005 using four different effort sharing criteria (adapted from Paper V). Error bars represent the variation range (min and max) in terms of percentage points of the criteria studied. The national GHG emission targets set by the EU (2009b) are illustrated by black circles. Countries furthest left have the largest variation between scenarios.

When looking at the requirements for improving the GHG intensity of economy in the non-ETS sector, the relatively fastest improvement was required in particular in Luxembourg, Ireland and some Eastern European countries, like Poland and Romania (Paper V). However, according to the scenarios, Ireland was the only country that came close to maintaining the historical rate on average. Latvia faced great GHG emission reduction requirements, if emissions were to be reduced based on reductions in GHG intensity in the past. Nevertheless, Latvia was allowed on average less improvement in annual GHG intensity than during 1993–2005. Slovakia, Romania and Poland faced the toughest GHG intensity reduction requirements in a scenario based on equal GHG per GDP criteria. For Sweden, UK, Finland and Denmark, the required effort was less than double the historical rate.

4.3.2 At the global level by 2050

Radiative forcing in 2100, calculated with the ETSAP-TIAM model, was 3.6 and 3.0 W/m^2 in target scenarios with the stabilization of the atmospheric GHG concentrations to 550 and 485 ppm CO_2-eq., respectively. The corresponding figures for the global mean temperature increase in 2100 were 2.1 and 1.8 °C. Depending on the emission reduction target scenario and the underlying socio-economic baseline scenario, the GHG emission allowances for Annex I[5] allocated by the Triptych and Multistage approaches varied from 10% to 50% reductions in 2020, and from 60% to 95% reductions in 2050 compared to the level of 2000 (Figure 5). Non-Annex I regions were allowed to increase their emissions up to 2020 by varying amounts, whereas in 2050 only the least developed regions received allocations above their 2000 emission levels. It should also be noted that the Multistage approach generally allocated more emissions to the least developed countries in 2050 than Triptych.

[5] Parties include the industrialized countries that were members of the OECD in 1992, plus the EIT countries, including the Russian Federation, the Baltic States, and several Central and Eastern European States.

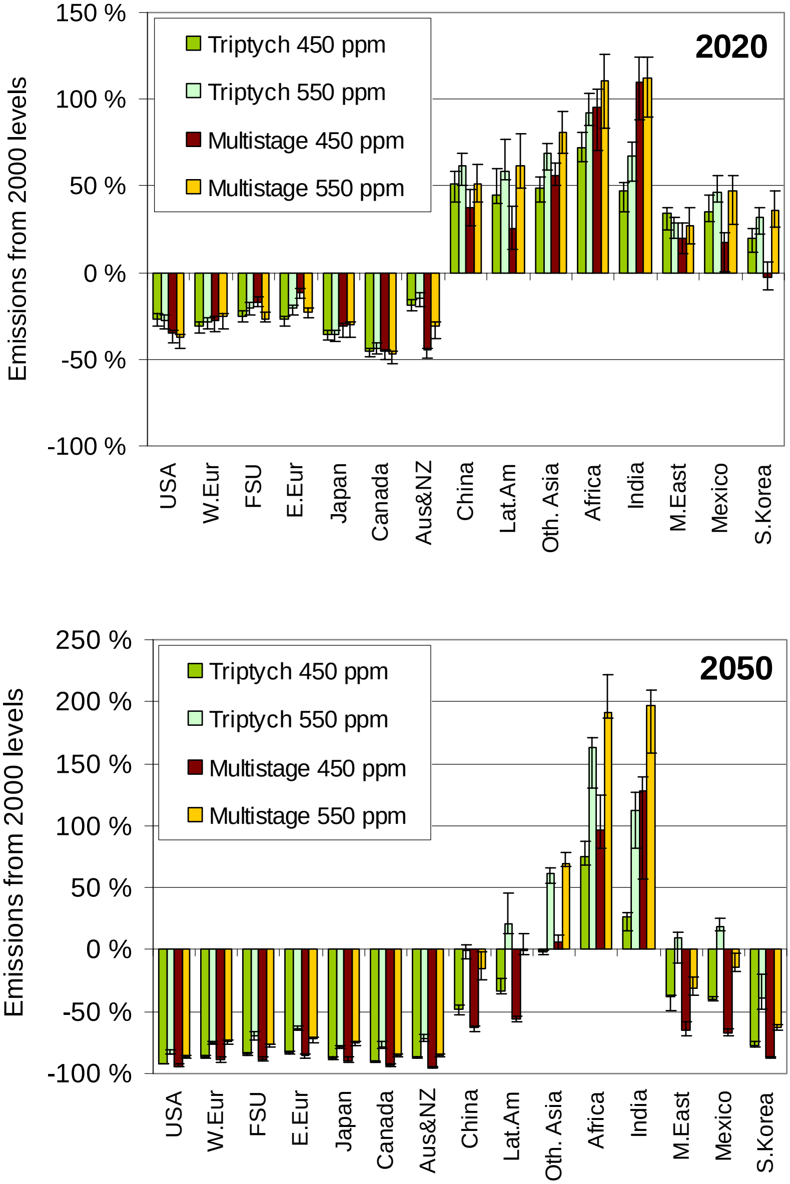

Figure 5. GHG emission allocation, relative to 2000 emissions, with the Triptych and Multistage effort sharing approaches with the 550 and 485 ppm CO_2-eq. stabilization targets in 2020 (up) and 2050 (down) (Paper VI). The error bars correspond to the range of values with four IPCC SRES baseline scenarios. (AUS&NZ = Australia and New Zealand, E.Eur = Eastern Europe, FSU = Former Soviet Union, Lat.Am = Latin America, M.East = Middle East, Oth. Asia = Other Asia, S.Korea = South Korea, W.Eur = Western Europe)

According to the analysis carried out using the ETSAP-TIAM model, the electricity sector provided the largest cost-efficient GHG emission reduction potential (Figure 6). The phase-out of coal and other fossil fuels with the large-scale adoption of wind power and bioenergy and also to some extent nuclear power and hydro power, and the use of combustible fuels in conjunction with CCS, contributed to most of the emission reductions. In addition, large emission reductions were made in the industrial sector and a number of measures were also introduced in the other sectors. The phase-out of fossil fuels and the use of CCS also played an important role in industrial emission reductions together with, among others, changes and improvements in industrial processes, such as an increased use of steel scrap or inert anodes in aluminium smelters and N_2O emission reductions using thermal destruction and catalytic reduction, respectively, in adipic and nitric acid industries. In road transportation emission reductions through a shift to natural gas, electricity/hydrogen and biofuels (when sustainably produced) were feasible. However, due to a rising demand for road and international transportation together with limited emission reduction potential for international transportation, the level of transportation emissions increased and remained approximately constant in the 550 ppm and 485 ppm scenarios, respectively. In agriculture the emission sources are very dispersed, often subject to major uncertainties and mostly concentrated on the rural areas of less developed countries. Consequently, it is difficult to control the emissions and effectively introduce enhanced practices, and thus only limited low-cost emission reduction potential is included in the model.

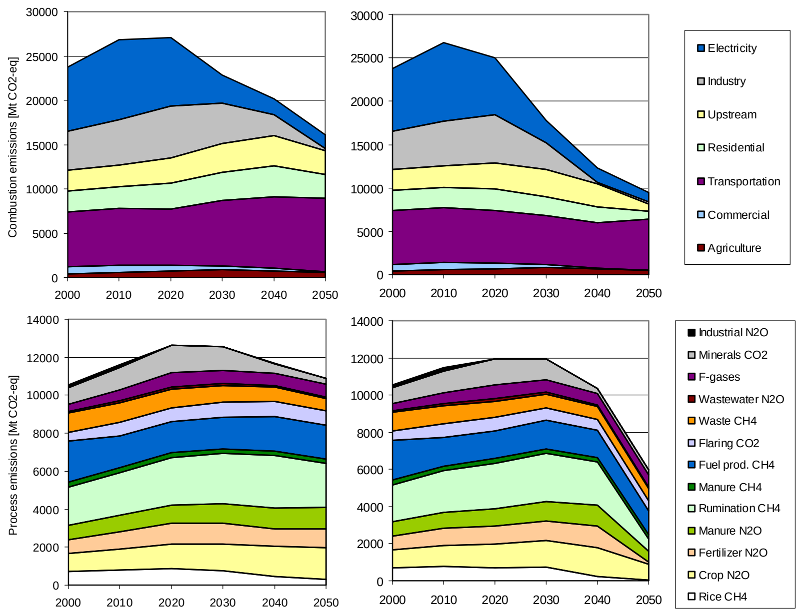

Figure 6. Global GHG emissions under the moderate growth B2 scenario with the 550 ppm (left) and 485 ppm (right) CO_2-eq. stabilization targets, split between combustion-based (top) and process-based (bottom) emissions (Paper VI). Non-CO_2 emissions converted to CO_2-eq. by using GWP-100 according to IPCC (1996).

The share of global emission reduction costs in GDP was approximately 0% in 2020 (less than 0.14% in all scenarios), and varied approximately from 1% to 2% and from 4% to 5% in 2050 in the 550 and 485 ppm CO_2-eq. scenarios, respectively, depending on the underlying socioeconomic baseline scenario. The marginal costs of emission allowances in 2050 rose as high as to 250–500 and 600–1000 USD2000/t CO_2-eq. in 550 and 485 ppm CO_2-eq. scenario, respectively.

Both Triptych and Multistage rules allocated costs for Annex I countries in 2020 (with the exclusion of Eastern Europe), costs around zero for more developed non-Annex I countries, and gains for least developed countries as a result of selling emission allowances (Figure 7). In 2050, Annex I countries, especially Australia and Russia (as a part of the former Soviet Union), faced relatively high costs in the 485 ppm CO_2-eq. target. Also, most non-Annex I countries faced positive costs, and only India and Africa were able to gain financially from the effort sharing. The costs for Annex I regions were generally doubled in the 485 ppm CO_2-eq. target in 2050 compared to the 550 ppm CO_2-eq. target. A clear outlier from the overall pattern with all effort sharing rules was the Middle East, in which the emission reduction costs arose to a large extent from lower revenues from oil trade.

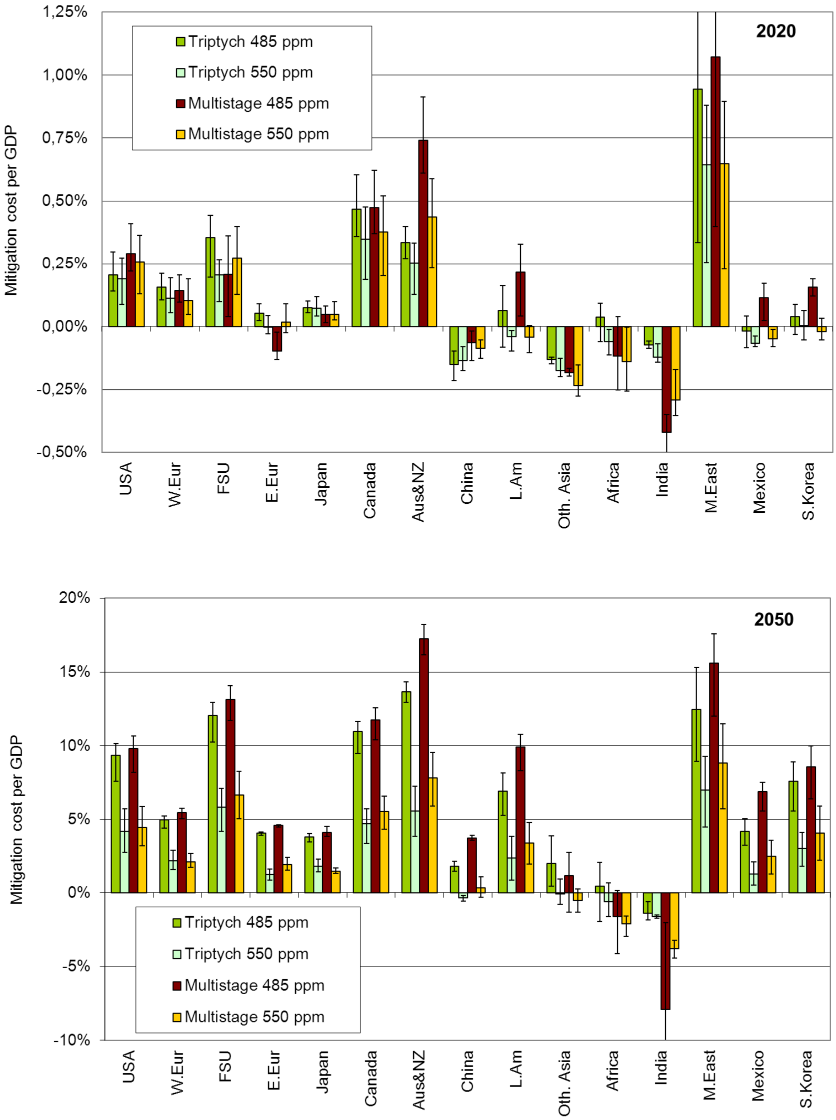

Figure 7. Regional GHG emission reduction costs relative to their baseline GDP in 2020 (up) and 2050 (down) (Paper VI). The error bars correspond to the range of values with four IPCC SRES baseline scenarios. (AUS&NZ = Australia and New Zealand, E.Eur = Eastern Europe, FSU = Former Soviet Union, Lat.Am = Latin America, M.East = Middle East, Oth. Asia = Other Asia, S.Korea = South Korea, W.Eur = Western Europe.)

5. Discussion

5.1 Attributing emissions and emission allowances

Attributional life cycle assessment (ALCA) aims to describe a product system as it is without aiming to capture the consequences of introduction, modification or decommissioning of the product system. Similarly, various criteria to differentiate emission reduction commitments at country or country group level such as Triptych and Multistage approaches aim to attribute emission allowances between the countries or country groups without regard to the consequences *per se*. The quality of data and criteria to attribute the potential emissions or environmental impacts and emission allowances in ALCA and effort sharing, respectively, are the critical underlying issues influencing the outcomes.

5.1.1 Emissions at product level

The sustainability criteria of the EU Renewable Energy Directive (RED) require, among others, determination of GHG emission reduction of transportation biofuels and other bioliquids compared to reference fuels. This should take place prior to or after the production of a certain quantity of the products. This can be done under certain conditions by using the default values given in the RED or by calculating the actual GHG emission saving compared to the reference fuels by using the given methodology. The assumptions used in determining the default values in the RED (BIOGRACE 2012) and in the specified RED methodology to calculate actual GHG emissions mostly follows the principles of ALCA as analysed in Paper II.

As presented in Papers I and II, the uncertainties of GHG emissions of biofuels may be very significant. Regional differences clearly create natural variation in results between different studies. For example, the GHG emission intensity of RME studied in Paper I was higher than in most of the studies reviewed by Malca and Freire (2011). Only a few studies (Reijnders and Huijbregts 2008, Harding et al. 2007) have arrived at a GHG emission intensity of the same magnitude as that presented in Paper I. The yield per nitrogen fertilizer requirement is relatively low in Finland mainly due to climatic conditions influencing, for example, the growing season, nitrogen transfer from soil to plants and thus also feasible plants (Peltonen-Sainio and Jauhiainen 2010, Peltonen-Sainio et al. 2007). For example, the typical ratio of yield per N-fertilizer use in Finland for oil plant (spring turnip rape in Paper I) cultivation is approximately 16 kg/kg, whereas it equals roughly 22 kg/kg in the EU-25 on the average (JEC 2011) and roughly 20 kg/kg in Southern Sweden (Ahlgren et al. 2009). However, regional differences only explain part of the differences in GHG emission figures. Significant variation may also take place, for example, due to the way the parameters are determined and considered. In a review of a number of studies concerning GHG emissions of RME in Europe, Malca and Freire (2011) noted that treatment of co-products and land-use modelling including N_2O and CO_2 emissions from soils were the key issues resulting in significant variation between the studies. Similarly, in Paper I, N_2O emissions from soil, GHG emissions from electricity production and soil carbon changes due to raw material harvesting were recognised as being particularly important. Comprehensive screening of the differences between various studies is challenging and would require detailed meta-analysis.

Deterministic default values of the RED do not include any uncertainty range, as presented in Figure 2. In addition, in May 2012 it was unclear how required parameters and the involved uncertainty are to be considered in the accounting of actual GHG emissions in the context of the RED. The default values of the RED exclude carbon stock changes in soil and terrestrial biomass (BIOGRACE 2012) and they are not specifically obliged to be included in the calculations of actual GHG emissions when land-use change from one land use class to another does not take place (EU 2009c). The exact determination of parameters is not specified in the RED, except for the general frames for emissions to be accounted and the fixed rule for allocation (EU 2009c) as well as information for accounting for land carbon stocks in the case of direct land-use changes (EC 2010c). This may lead to significant differences in the determination of the actual GHG emission saving values of various biofuel chains.

Emissions are always generated in comparison to some reference situation. Typically, in ALCA the reference level is the absence of the use of resources (“no use”) generating the emissions (e.g. fossil fuels). However, regarding land use the reference situation is dynamic. According to a framework for LCIA of land use released within *The UNEP-SETAC Life cycle initiative* (Milà i Canals et al. 2007), in ALCA the “no use” reference situation is the natural relaxation of the land area. In practice, the determination of GHG emissions from the “no use” reference situation should always be based on assumptions which cannot be measured or monitored, creating an element of uncertainty. The determination of the reference situation for land use is not specified in the RED.

GHG emission reductions are often measured in relative terms compared to a reference functional unit (e.g. the use of fossil fuels to produce the same functional unit). In many recent studies concerning biofuels, and in the RED methodology, the relative emission reduction indicator is determined as the difference of the GHG emission balance between the fossil reference fuel and the biofuel compared to the fossil reference fuel (see Equation 1). The fundamental problem of this particular kind of ‘relative emission reduction’ indicator is the inability to measure the effectiveness of biomass utilisation as a measure to reduce GHG emissions.

The relative GHG emission savings may look particularly favourable for biofuel processes in which significant amounts of low GHG emission intensive raw materials are used in relation to the amount of biofuel produced. At the same time, another process for converting biomass to biofuel in a more energy-efficient way, while using more fossil resources, may appear unfavourable in terms of the particular indicator. The effectiveness of use of the limited resources – biomass and land – is excluded when using this kind of ‘relative emission reduction’ indicator. Consequently, this particular indicator cannot be used to compare GHG emission reductions between different end-use options for biomass, for example transportation biofuel and electricity production. In order to promote the most efficient options of biomass and land use in climate change mitigation, other kinds of ‘relative emission reduction’ indicators may be more appropriate. It would be reasonable to measure the GHG emission balances or savings of biofuels in terms of the limiting factors, for example biomass, land area or money spent (Schlamadinger et al. 2005). ‘The relative emission reduction’ indicator presented in Figure 1 takes into account the biocarbon consumed for the emission reduction.

The determination of GHG emissions is a key issue concerning electricity consumption of product systems in ALCA, for example in the production of biofuels in the context of the RED. As presented in Section 4.2, the annual variation, selection of allocation method and consideration of electricity trade between countries significantly influence the annual average CO_2 emission intensity of electricity in many countries. In Papers III and IV, the use of the consumption-based method is advocated in preference to the production-based method for LCA purposes. However, the use of one allocation method as superior to others cannot be suggested based on the results of Paper IV. As presented in Section 3.1.1, the allocation should primarily be avoided whenever possible or be based on physical causal relationship of the products. If this cannot be done, the allocation can be based on other relationship of the products. As physical causalities cannot be determined to CHP plants, which are built to jointly produce electricity and heat (Frischknecht 2000), a non-causal-physical relationship needs be used as a basis for allocation. In Paper IV, allocation based on energy content and ‘motivation electricity’ was selected to represent the lower and the upper boundary of the range, respectively, of the CO_2 emission intensity of electricity. Both of these methods are applied in practice. In the RED methodology allocation is determined to be based on lower heating value of the products in case no biofuel production is related to the electricity production. Regarding CHP, this probably means the use of ‘the motivation electricity’ method as heat does not have lower heating value. On the other hand, allocation based on energy content of the products is suggested for CHP in the *Energy Statistics Manual* jointly produced by IEA and EUROSTAT (IEA 2004). As presented in Papers III and IV, the use of only one allocation method may be highly misleading. When allocation cannot be avoided, and if only one particular allocation method is to be applied, an allocation based on economic value is suggested as the most suitable option (Guinée et al. 2004). In addition, Ekvall et al. (2005) concluded that allocation should be based on the economic value of the products when the aim of the study is to describe the causes of the environmental burdens of the life cycle in ALCA. The allocation method presented in the RED is not consistent with these conclusions.

The figures presented in Section 4.2 for CO_2 emission intensities of electricity consumption do not include upstream emissions from supply of the fuels and production of the infrastructure and power plants. These, however, typically constitute a relatively low share of GHG emissions of the overall electricity production mix (e.g. Kim & Dale 2005, Santoyo-Castelazo et al. 2011, Lee et al. 2004), although for certain power production technologies they may be significant (Frischknecht et al. 2007, Weisser 2007). However, an extensive shift in energy production systems may occur within the next few decades with the large-scale introduction of low GHG emission intensive power production technologies as a result of ambitious climate change mitigation targets (IPCC 2007c). Consequently, in the overall life cycle of electricity consumption, the contribution of GHG emissions other than direct CO_2 emissions from fuel combustion might increase significantly, and would therefore need to be considered more carefully. In particular, GHG emissions related to the cultivation and harvesting of bioenergy have already been widely discussed. Also, CH_4 and N_2O emissions from fuel combustion should be considered and they may play relatively significant role for some combustion technologies (Tsupari et al. 2005, 2007).

The definitions of spatial and temporal system boundary for the electricity production mix are crucial issues. Apart from annual national average mixes, smaller or larger regions and shorter and longer time frames may also be selected. As discussed in Paper III, figures based on the contract between the electricity seller and the customer with real-time accounting would be the ideal production mix figures for history-related ALCA. A general introduction of this kind of 'contract-based' approach would eliminate the prevailing problem in selecting the spatial and temporal dimension arbitrarily. Currently, such data and respective reporting practices do not generally exist, and thus further research and agreements between various stakeholders are required. For future-related ALCA studies, the development of the power production system should be considered by using an appropriate scenario analysis.

Ideally all environmentally relevant physical flows from the cradle to grave of a product system are included in ALCA. In practice it is constrained by time and resource limitations, and parts of the system, such as services and capital goods, are usually ignored or cut off from the analysis. The impacts of the neglected parts on the GHG emission results may vary significantly depending on the system (Suh et al. 2004, Ferrao & Nhambiu 2009, Mongelli et al. 2005, Mattila et al. 2010). Approaches to consider potential environmental impacts of flows which are not necessary included in LCA based solely on process description (process-LCA) are so called input-output-LCA (IO-LCA) without using any process-based life cycle inventories and hybrid-LCA combining both process-LCA and IO-modelling (Suh 2004, Suh & Huppes 2005, Hendrickson et al. 2006). The question whether available databases of IO with environmental extensions are robust enough has been raised and progress to improve the quality and applicability of the data is being made in various countries (Finnveden et al. 2009).

5.1.2 Emission allowances at country level

The effort sharing of national (non-ETS) emission targets of the EU Member States in 2020 were studied in Paper V. Unanimous annual reduction, historical development and convergence in GHG/GDP as well as GHG/capita convergence were applied as a basis for sharing emission targets. The emission reduction requirements for a given country varied significantly depending on the criterion applied, which confirms the findings of den Elzen et al. (2007). Furthermore, changes in underlying assumptions, such as the selection of the base year applied, the allocation of GHG emission reductions between the ETS and non-ETS and the choice of GDP forecasts, as studied in the sensitivity analysis in Paper V, posed significant variation in the results.

Triptych and Multistage approaches were studied for global effort sharing in Paper VI. Both approaches allocated emission reductions to the 15 regions studied very differently, in particular for non-Annex I countries. In general, compared to Triptych, the Multistage approach allocated clearly more emission allowances to the least developed countries due to assumed later participation in the binding commitments. The baseline scenario and the overall emission reduction target also significantly influenced the results. Also, the accuracy related to historical GHG emissions applied as a basis for assumed future baseline emissions of Triptych and Multistage played an important role. Using different historical emission estimates (e.g. change from the UNFCCC data to IEA/EDGAR data) might imply differences of several tens of percentage points on the allowances a country receives (Paper VI). Furthermore, the other assumptions used in Triptych and Multistage approaches to set emission reduction targets for the countries certainly influences the results, although this is not studied in Paper VI. For example, Soimakallio et al. 2006 concluded that, although sensitivity analysis carried out for the Triptych 6 and Multistage approaches for some methodological assumptions indicated a relatively low variation compared to the impact of baseline scenario, more methodological changes might have resulted in more significant variation. The recalibration of the EVOC tool that was carried out in Paper VI resulted in large changes in the emission allowances allocated by the Triptych to certain countries, especially for Australia in 2050, highlighting clearly the importance of assumptions used in the effort sharing process.

5.2 Capturing consequences

Consequential life cycle assessment (CLCA) aims to describe at product system level how environmentally relevant physical flows would have been, or would be, changed in response to possible decisions that would have been, or would be, made. Similarly, bottom-up modelling can be used to assess consequences taking place at sector, national or global level due to various decisions, such as targets to mitigate climate change and emission reduction effort sharing. For both types of assessment of consequences a number of assumptions are required. The fundamental problem is the difficulty in identifying the change from the reference scenario due to a complex cause and effect relationships.

5.2.1 Increased production of biofuels

The analysis of Paper I followed the principles of CLCA. (However, Malca and Freire (2011) classified the method used in the particular paper as ALCA with no specified explanations). The results for GHG emission reduction of replacing reference fuels by biomass-based transportation fuels, electricity and/or heat in Finland reflected significant parameter uncertainties. Nitrous oxide emissions from soil, soil carbon losses, emissions from electricity production and emission reduction from replaced electricity were the most significant parameters, depending on the biofuel chain considered (Table 2). The uncertainties in other individual parameters had a clearly minor influence on the overall uncertainty range. The type of probability distributions were selected subjectively in Paper I, and the uncertainty due to that selection was not studied. Instead, Plevin et al. (2010) tested a range of various types of probability distributions, and concluded that the shapes of the probability distributions studied had relatively little effect on the shape of the output frequency distribution in their case study. However, this conclusion cannot be directly applied to the analysis carried out in Paper I, and should therefore be studied.

Also, the other assumptions used in CLCA are of central importance. In Paper I, it was assumed that land and raw materials were available for biofuels. However, this is not necessarily the case in practice. As discussed in Paper II, the taking of agricultural land for biofuel raw material production may transfer other agricultural activities indirectly elsewhere. The consequences may be very far reaching in space and time, including deforestation and significant carbon dioxide emissions (e.g. Searchinger et al. 2008, Plevin et al. 2010, Edwards et al. 2010). There is support for the assumption that an increase in soy in, for instance, Mato Grosso, Amazonia, has displaced pasture, leading to deforestation elsewhere (Barona et al. 2010). According to IPCC (2011), the significance of land-use changes (LUC) on GHG emissions of products was demonstrated in the 1990s when direct land-use changes (dLUC) effects were introduced in some life cycle assessment (LCA) studies (e.g. Reinhardt 1991, DeLucchi 1993). However, most LCA studies have not considered indirect land-use changes (iLUC) taking place through market mechanisms (IPCC 2011).

In recent years, a number of studies aiming to analyse dLUC and iLUC related to the increasing production of biofuels have been conducted. The simplest approaches to estimating predicted iLUC are based on aggregated recent historic data on biofuel feedstock determination and agricultural expansion, combined with assumptions on a number of crucial future-related parameters such as feedstock, co-product availability, likely LUC types and the associated lost carbon stocks (Cornelissen et al. 2009). Such approaches include the ones presented by Fritsche (2007), Ecometrica (2009), Scott-Wilson (2009) and Overmars et al. (2011). Over the past few years, the quantification of iLUC related to biofuels has mainly been carried out using various types of economic and environmental models jointly (e.g. Searchinger et al. 2008, Al-Riffai et al. 2010, Birur et al. 2008, Fabiosa et al. 2010, Edwards et al. 2010, Plevin et al. 2010). General scientific consensus exists on using an economic approach to address iLUC, but the methods are generally controversial (Kim & Dale 2011, O'Hare et al. 2011, Kline et al. 2011, Gnansounou et al. 2008). The results of an economic approach are highly sensitive to the assumptions used. For example, Barona et al. (2010) concluded that the drivers of Amazon deforestation need further research on how interlinkages between land area, prices and policies influence cultivation and deforestation. Furthermore, improvement of land-use modelling in PE energy system models and GE economic models, or more integrated modelling using such models and land-use models together are required to better assess the consequences related to expanding biofuel production. Plevin et al. (2010) concluded that, although the emissions from iLUC are subject to significant uncertainties, the emissions take place and there is a significant likelihood of large emissions.

Additionally, the competition of forest-based raw materials may cause remarkable indirect impacts. Forsström et al. (2012) concluded, based on partial equilibrium energy system modelling, that the introduction of large-scale production of transportation biofuels from forest-based raw materials in Finland would lead to significant re-allocation of wood use from other energy production and industry, thus increasing the use of other fuels in those sectors. Furthermore, they concluded that re-allocation of wood use from electricity and/or heat production to transportation biofuel production would result in an increase in GHG emissions in Finland. This emphasises the conclusion drawn, for example, by Ohlrogge et al. (2009) that greater reductions in GHG emissions can be achieved by using raw materials for power or heat production to substitute coal than by producing more energy intensive liquid biofuels to substitute oil.

Apart from the spatial dimension, also the temporal dimension of a system boundary is critical. In static temporal assessment, all GHG emissions and sinks are assumed to take place at the same time and they are then equalised over the lifecycle studied, resulting in model uncertainty. The exclusion of dynamics of the GHG emissions, sinks and avoided GHG emissions is problematic, particularly when they differ significantly over time, which may be the case for many bioenergy options (Kendall et al. 2009, Cherubuni et al. 2011). This is the case in particular when significant pulse emission takes place due to immediate land-use change (Kendall et al. 2009), or relatively slowly grown forest biomass is used (Pingoud et al. 2011). In Paper I the soil carbon losses due to logging residue harvesting were considered by estimating the amount of carbon that would have been accumulated into soil after 100 years in a reference situation. Even though capturing one dynamic dimension in Paper I, the particular approach does not take into account the fact that the carbon dioxide released from biofuel combustion compared to the reference situation is to be accumulated in the atmosphere, resulting in positive radiative forcing. Capturing the particular effect by using dynamic indicators such as those presented by Kirkinen et al. (2008, 2010) or derivates of them (e.g. the one presented by Pingoud et al. 2010, Repo et al. 2011 or Kujanpää et al. 2010), would result in an increase in the GHG impact of soil carbon losses over 100 years by approximately 30% compared to the figure applied in Paper I (Kujanpää et al. 2010). Furthermore, different time frames result in different conclusions. For example, applying 20 or 50 year timeframe results in significantly greater impacts compared to applying 100 year timeframe (Kirkinen et al. 2010, Pingoud et al. 2011, Repo et al. 2011, Kujanpää et al. 2010). The fundamental problem is that there exists no unique scientifically defined robust timeframe, rather the temporal dimension is a value-based issue reflected by the emphasis of contemporary climate policy.

In Paper II, the suitability of the RED methodology for ensuring GHG emission reductions of increasing production and the use of transportation biofuels and other bioliquids in practice are analysed and discussed. In the RED (methodology), all types of indirect effects through market mechanisms and the possible losses in soil and temporal carbon stocks are excluded in the determination of the default values and in the methodology to calculate actual GHG emissions. Consequently, there is a serious risk that the sustainability criteria of the RED underestimate the GHG emission impacts related to large-scale biofuel production and may promote biofuels with low reduction or even an increase in the overall GHG emissions and prevents biofuels with higher benefits at the same time.

5.2.2 Grid electricity consumption

Regarding electricity consumption or conservation in CLCA, the major challenge is to identify the marginal technology, and furthermore, the consequences influenced by the change (Paper III). In its simplistic form, marginal production, affected by the marginal change in the electricity consumption, is identified. Large variations between the affected technologies may occur. Using fundamentally different kinds of affected technologies for this kind of analysis has been suggested (Mathiensen et al. 2009). However, the instant marginal GHG emissions of electricity production do not reflect the market effects beyond the immediate change. Such effects may take place in the short term (e.g. increases in electricity price) and long term (e.g. investment decisions). The anticipated development of energy prices, quantity and time-dependent profile of electricity consumption as well as climate policy are probably the most important market drivers of new investments in electricity production (Lund et al. 2010). The range applied for GHG emissions of marginal electricity consumption (0–900 g CO_2-eq./kWh) in Paper I fits quite well with the long term marginal technology mix presented by various papers cited and discussed in Paper III. Furthermore, the range (300–900 g CO_2-eq./kWh) applied to electricity consumption replaced by biofuels in Paper I can be justified by the fact that the targets for increasing the use of renewable energy sources in the EU are so massive that it is very unlikely that the use of renewable energy sources will be replaced by bioenergy. Thus, the lower limit can be considered to reflect the replacement of the use of the low GHG emission intensive fossil fuel that is relatively efficient natural-gas-fired condensing power.

As changes in the power system are not isolated, electricity consumption and production cannot be separated from one another (Lund et al. 2010). When attempting to study the consequences of a decision to change electricity consumption on GHG emissions, an improved understanding of the phenomenon is certainly required. It is important to recognize that, not only the electricity production system is affected, but probably many other economic activities as well. Scenarios that depict the changes in economic inputs and outputs can be constructed using economic equilibrium models (e.g. Manne et al. 1995, Nordhaus 1999, Nijkamp et al. 2005). Yet, due to the complexity of such models, the energy system is typically described in relatively rough terms, limiting the suitability of such models for assessing, for example, GHG emission impacts. Partial equilibrium models for energy systems such as ETSAP-TIAM used in the analysis of Paper VI and others presented e.g. in Lund et al. (2010) and Klaassen & Riahi (2007) can provide detailed information on the development of energy production in supplying external energy demand. By using economic equilibrium and partial equilibrium models simultaneously, it is possible to create far-flung scenarios to determine the development of GHG impacts of the economies and various actions. Yet, scenarios always involve a certain degree of uncertainty. Consequently, it is suggested that an appropriate number of scenarios are carried out for CLCA in order to provide adequate perspectives on the evolution of the economies, electricity consumption and production as well as GHG emissions under various relevant market conditions.

5.2.3 Costs of effort sharing

The direct impact of emission reduction effort sharing is the distribution of the emission reduction costs between the countries. In Paper V costs resulting from the application of various effort sharing scenarios studied were not considered. In Paper VI the economic burden of emission reductions was shared through the allocation and trade of emission allowances. Thus, the price of allowances became a critical factor for the costs the countries faced. Besides depending on the effort sharing the price of allowances also depends on the direct emission reduction costs. The baseline scenario and descriptions of cost-curves and potentials of technologies furthermore affected the marginal abatement curve (MAC) of a country. This can be noted by reflecting the results presented in Paper VI to other comparable studies (e.g. den Elzen et al. 2008b, van Vuuren et al. 2007). The global costs between the studies were quite similar, but the marginal costs in comparable studies were lower compared to those presented in Paper VI, in particular due to more pessimistic assumptions used for non-CO_2 emission reduction and bioenergy supply potentials in the ETSAP-TIAM model. Uncertainties of MACs are much larger in the more ambitious 485 ppm CO_2-eq. scenario, in which more unconventional emission reduction measures have to be taken in order to reach the emission target compared to 550 ppm CO_2-eq. scenario. The effect of technological and resource uncertainties on effort sharing might, however, be minor, as most technologies affect all countries (den Elzen et al. 2005). On the other hand, den

Elzen et al. (2008b) noted that a specific technology cost, CCS's in their case, might affect some countries more than others. Allowance prices might also carry additional uncertainty due to market imperfections as studied in the sensitivity analysis of Paper VI.

The partial equilibrium approach used in Paper VI, while providing a detailed picture of the direct emission reduction costs, does not include any feedback effects from the rest of the economy. Effort sharing, especially in the extreme cases, might involve large wealth redistributions through allowance markets, affecting affluence levels and energy demand. Furthermore, a high price of emissions is likely to induce structural change in the economy. Should the demand and production structures adjust to the cost of carbon, the mitigation costs would then be lower than reported here. With the ETSAP-TIAM model, the only possible adjustment is reduced demand (i.e. welfare loss) instead of, for example, demand substitution. What is more, the avoided damage costs from climate change through mitigation were ignored. To provide a broader picture of the costs and avoided costs, wider economic and risk assessment analyses are required through CBA.

5.3 Avoiding emission leakage

GHG emission leakage takes place when the consumption of goods and related production are geographically separated. Weak definition of leakage considers the total aggregated GHG emission flows embodied in trade, typically from non-Annex B to Annex B countries with binding emission reduction targets under the Kyoto Protocol (Peters & Hertwich 2008). Strong carbon leakage is used when policy change in an Annex B country causes production to increase in a non-Annex B country (ibid.). According to Peters et al. (2011), the net CO_2 emission transfers from developing to developed countries exceeded the GHG emission reduction targets of the developed (Annex I) countries in the Kyoto Protocol.

Global commitment into country-specific emission caps as studied in Paper VI would significantly reduce or even avoid the risk of emission leakage. Even though developing countries were allowed to increase their emissions in 2020 and the least developed countries even in 2050, the commitment to a cap-and-trade system would prevent the possibility of unlimited emission growth in non-Annex B countries. However, as there is no agreed systematic approach for effort sharing, for example based on certain criteria, under the UNFCCC, the international climate negotiations are completely dependent on pledges given by the countries. The risk of significant GHG emission leakage between countries exists at least as long as a comprehensive and effective climate convention is lacking.

One solution for reducing significant emission leakage could be the introduction of consumption-based emission targets for countries or products based on an end-use responsibility point of view (Pingoud et al. 2010). The sustainability criteria for transportation biofuels and other bioliquids of the EU are an example of this kind of approach. However, exclusion of indirect impacts from the system boundary considered, as in the case of the EU RED, would not remove the problem of emission leakage. One option for reducing indirect impacts could be the use of certain types of wider average data instead of case-specific data, for example related to land-use changes, as suggested in Paper II and by Saikku et al. (2012). In such an approach, indirect impacts are moved from the consequential framework to be an attributional issue by extending the system boundary for emission attribution. Another option would be the extensive introduction of consumption-based criteria not only for certain applications such as biofuels but for various products. Ideally, if all the products were monitored, no unmonitored indirect impacts would take place. However, consumption-based determination of emissions encounters the problems of life cycle assessment, which makes it difficult to find a consensus between a number of parties or stakeholders as to the practical solution. In addition, the countries that are not ready to take binding national emission caps would be unlikely to commit their industry to binding consumption-based targets either.

5.4 Equity issues

Different types of perspectives on equity are encountered in LCA and emission reduction effort sharing. Fundamentally, there is a dilemma between undesirable environmental consequences and responsibility. In LCA, there is a need to select between an attributional and a consequential approach and the related system boundaries, between average and marginal data, and between various allocation methods. In effort sharing, the criteria and data to be applied need to be defined. The selections may be considered fair or unfair from various points of views.

The technical limitations of subjective choice of system boundary setting and other methodological choices in LCA have equitability implications. For example, the cut off rule to exclude the emissions from the construction of machinery and infrastructure and the rule not to allocate emissions to co-produced heat, applied likely in the EU RED methodology, may be considered unfair to fuel producers or other stakeholders, especially if they would have played an important role in the GHG emission reduction results of a product. Arbitrary determination of appropriate average data to be used in ALCA is also problematic. The use of average data instead of case specific data, for example related to the determination of appropriate electricity production or land-use mix, may be unfair to those actors doing significantly better environmentally than the average level. On the other hand, the use of case specific data may be considered unfair to those actors not having an opportunity to use the particular resource, as it includes an assumption of the right to use certain resources regardless of their availability. CLCA is subject to inherent uncertainty, as it is not possible to consider all the impacts and the uncertainty in the marginal effects increases with the time horizon.

Apart from technical limitations, both ALCA and CLCA also have endogenous ethical limitations. According to Ekvall et al. (2005), ALCA (retrospective in their typology) is consistent with both deontological[6] and teleological[7] rule ethics, whereas CLCA (prospective in their typology) is valid from the perspective of teleological situation ethics. The RED sustainability criteria for transportation of biofuels and other bioliquids seem to reflect a special case of deontological and teleological rule ethics. The rule adopted in the criteria does not have links to all of the consequences (e.g. indirect impacts), but is introduced so as not to be associated with systems that have undesirable climate impacts (e.g. direct deforestation). If the RED sustainability criteria were modified to better include the consequences, for example iLUC (EC 2010d), this could be an example of how CLCA generates the information that is relevant in the context of teleological rule ethics. ALCA includes a risk of unaccounted undesirable consequences, whereas CLCA holds a risk of unfair results and suboptimised systems (Ekvall et al. 2005), raising the question of the responsibility of the marginal effects. One example is the question of whether the 'new electricity consumption' should be considered differently (e.g. by using marginal data) from 'the existing one', and if so, what are the implications of using this information in decision-making.

The choice between an attributional and a consequential approach is significant, though from a certain point of view they can both be considered equitable and legitimate. When aiming to avoid life cycles and subsystems that have an undesirable environmental impact, ALCA is useful in decision making. Similarly, if the changes in product systems are considered 'good' if consequences for the total environment are lowered, then CLCA is valid (Ekvall et al. 2005). From the perspective of utilisation of LCA results by, for instance, consumers or policy-makers, it can be considered unfair if the results are not reported in the light of goal and scope of the study. The major uncertainties and sensitivities involved, as well as the limitations of the applicability of the results, should be reported. The goal by definition in LCA should not be to assess everything exactly at the most detailed level, but to create relevant information for decision-making.

Equity is a fundamental but also an ambiguous issue in emission reduction effort sharing. For example, Ringius et al. (1998) define five different equity concepts: 1) Egalitarian (equal emissions per capita), 2) Sovereign (equal emission reductions from e.g. 2000), 3) Horizontal (equal net change in welfare e.g. in GDP), 4) Vertical (effort depending on ability), 5) Equal responsibility (effort based on historical emissions). Different effort sharing criteria follow different equity principles and result in different implications. Ultimately, the effort sharing under the UNFCCC will be a result of political climate negotiations in which a systematic effort sharing approach may either be used or not. There is no definitive answer to the equitable balance between the costs and gains of different parties, but a quantified assessment of possible outcomes might aid the process considerably. One

[6] The normative ethical position that judges the morality of an action based on the action's adherence to a rule or rules.

[7] Ethical theory that holds that the consequences of an act determine whether an act is good or bad.

major problem is that the costs can be assessed by using various assumptions concerning, for example discounting and exchange rates of currencies, and from very different perspectives, including or excluding social costs, which are very important but typically subject to significant uncertainties compared to direct costs (Tol 2003). On the other hand, if a consensus in effort sharing is found, it could be considered to be an equitable solution.

5.5 Climate impacts, sustainability and multi-criteria decision-making

In this study, GHG emissions, avoided GHG emissions and associated direct costs were considered as well as climate impacts in terms of global mean surface temperature increase. Other possible types of climate impacts such as sea level rise, floods, droughts and diseases were excluded, as well as other types of impacts influencing radiative forcing such as albedo changes through land-use changes, aerosols and black carbon on snow. These issues may be very important but they are also subject to remarkable uncertainties (IPCC 2007a, b). Furthermore, climate sensitivity to increasing concentrations of GHGs is highly uncertain (IPCC 2007a). Consequently, more information is required in order to more reliably assess overall warming and follow the climate impacts of various measures or emission paths.

As discussed in Section 5.2.1, in the context of carbon stock changes, the time frame in which the climate impacts or climate change mitigation are considered is highly relevant. Typically, various non-CO_2 GHG emissions are characterized as carbon dioxide equivalents by using GWP-100 factors, which are officially used in annual GHG emission reporting to the UNFCCC and the Kyoto Protocol. However, the time frame is critical when weighting cumulative radiative forcing of different GHGs, as they have significant differences in their specific infrared absorption properties and atmospheric lifetimes which are, furthermore, subject to uncertainties (IPCC 2007a). For example, the use of 20-year time horizon instead of 100 years roughly triples the global warming potential of CH_4, whose atmospheric life time is only some 12 years. Furthermore, the uncertainties of the direct GWP factors provided by the IPCC are estimated to be ±35% for the 5 to 95% (90%) confidence range. (Ibid.)

Apart from GWPs with various time frames other types of metrics have also been proposed to characterize various GHG compounds. The global temperature change potential (GTP) is a physical metric that compares the global average temperature change at a given point in time resulting from equal mass emissions of two greenhouse gases (IPCC 2009). As the assumptions on climate sensitivity to radiative forcing and the exchange of heat between the atmosphere and the ocean are included in GTP, greater uncertainty is involved in the particular metrics compared to GWP. Substantial work has also been performed on metrics that combine physical and economic considerations, such as global damage potential (GDP) and global cost potential (GCP) (IPCC 2009).

When comparing the emissions of gases with substantially different lifetimes, the choice of metric becomes very important. Compared to CO_2 emissions, the choice of metric has much greater implications for CH_4 than for N_2O, whose atmospheric lifetime is more akin to the lifetime of CO_2 (IPCC 2009). No single metric can accurately consider and compare all the consequences of the emissions of different GHGs. Thus, the most appropriate metric and time frame depend on the purpose and aims of climate change mitigation, which may, for example, be the limitation of global equilibrium surface temperature increase, limitation of global surface temperature gradient or limitation of instant surface temperature.

Apart from climate impacts, sustainability is a broader issue which has environmental, economic and social dimensions. Sustainability is a capacity to endure, which means for humans the long-term maintenance of responsibility. According to the most quoted definition, sustainable development (currently usually known as sustainability) "is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).

As regards the environmental dimension, sustainability requires methods and tools to measure and compare the environmental impacts of human activities for the provision of goods and services (Rebitzer et al. 2004). Human actions constitute a diverse range of emissions and resource consumption contributing to a wide range of impacts, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use and noise (Rebitzer et al. 2004). Today there is acceptance in the LCA community that the protection areas of Life Cycle Assessment are human health, natural environment, natural resources and to some extent the man-made environment (Udo de Haes et al. 1999, 2002). Impacts on the areas of protection are modelled applying the best available knowledge about relationships between interventions in the form of resource extractions, emissions, land and water use, and their impacts in the environment (Finnveden et al. 2009). A distinction is made between midpoint and endpoint, where endpoint indicators are defined at the level of the areas of protection, and midpoint indicators indicate impacts somewhere between the emission and the endpoint. Endpoint modelling is more reliable for certain impact categories such as acidification, cancer effects and photochemical ozone formation, while it is still under development, for example for climate change due to large uncertainties and the long time horizons of the endpoint (Finnveden et al. 2009). In addition, certain impact categories may include several types of impacts. An example is land use which can be separated among others into loss of biodiversity, loss of soil quality and loss of biotic production potential (Milà i Canals et al. 2007, Udo de Haes 2006).

Utilisation of LCA results in decision making requires the weighting of various environmental indicators. Furthermore, in many real life situations, LCA results are not the only criterion on which the decision is made. As regards sustainability as a whole, economic and social dimensions should also be taken into account and be weighted towards each other and various environmental indicators. Work has been done to integrate the three dimensions of sustainability through development and analysis of various methods such as life cycle costing (LCC) and social life cycle assessment (SLCA) (see e.g. CALCAS 2009). Weighting requires the inclusion of social, political and ethical values which are influenced by the perception of outcomes from science.

Multiple criteria decision analysis (MCDA) is used in the weighting of various indicator results into an overall sustainability score (Finnveden et al. 2009). In MCDA, the utility model consists of multiple decision criteria with subjective weights describing the relative importance of the criteria and decision alternatives and their performance with respect to each decision criterion (e.g. Saaty 1980, Keeney & Raiffa 1993). The decision-making problem depends on the uncertainty of LCA indicators, but also significantly on the weighting of the indicators and the related uncertainty (Mattila et al. 2012). In general, it cannot be determined whether the uncertainty of a single LCA indicator is significant, and whether the LCA is adequately reliable or not. For example, the choice from among various production methods for a product depends on the uncertainty level, the difference in the average utility ratios of the alternatives and the attitude of the decision-maker to risk (ibid.). It is possible that the weighting issues should be decided upon in advance, since it is not necessarily meaningful to carry out detailed, complex, comprehensive and probably costly uncertainty analysis if the relevant LCA indicator is given low weight in decision-making (ibid.).

6. Conclusions and recommendations

This study showed that there are significant uncertainties involved in the GHG emissions of biofuels and grid electricity consumption at product level and in the effort sharing of GHG emission reduction commitments at country or country group level. Parameter variation and stochastic simulation, successfully used in this study, are valid methods for propagating parameter uncertainties. However, the results provided by such methods should not be overinterpreted, as the results of any life cycle assessment (LCA) or effort sharing are only valid with the assumptions made.

Scenario analysis and parameter variation related to methodological choices needs to be carried out in order to understand the importance of the selections. Furthermore, the uncertainties due to modelling, for example through avoidance of the temporal dimension when accounting biomass-based carbon emissions to and sequestration from the atmosphere, may be of central importance. Although uncertainties may be great and the importance of including them in LCA has long been recognized (Heijungs & Huijbregts 2004), they are still often ignored in LCA studies (Finnveden et al. 2009). Similarly, most of the studies concerning differentiation of emission reduction commitments between countries (e.g. Phylipsen et al. 1998, den Elzen et al. 2005, 2006, 2007, 2008a, b, Höhne et al. 2005, 2006) have not conducted uncertainty analysis in a comprehensive manner.

In climate change mitigation, greater attention should be paid to uncertainties related to various emission reduction measures, in order to promote primarily the most certain ones. If the precautionary principle is followed, more conservative rather than optimistic estimates of emission reduction potentials of technologies should be used. The emission leakage has increased and became a serious risk to the effectiveness of climate policy and emission reductions implemented, for example, in the EU. Agreement on a comprehensive climate convention with ambitious emission reduction targets would lower the emission leakage risk significantly. An equitable solution in effort sharing is one of the major barriers to the success of international climate negotiations. If such an agreement cannot be achieved, the role of introducing consumption-based criteria and/or emission regulation at product level increases.

It is reasonable to ask whether the LCA is ready to move from an analysis tool to a decision tool such as the one applied in the context of the EU sustainability criteria for transportation biofuels and other bioliquids (RED). Applying the RED methodology to select the biofuels to be promoted in the EU cannot ensure that GHG emissions are reduced, as the consequences are not captured by the methodology. Careful consideration of market effects through resource competition should be carried out by using system level analysis. An integrated use of models with specific advantages is suggested. General and partial equilibrium models may be used to describe the interlinkages of energy and land use under the given economic conditions to generate more robust GHG emission scenarios that can be further analysed by climatic models. When the target is to reduce emissions, it is not necessarily important to model everything exactly, but to create incentives which lead to appropriate consequences.

The results of an LCA and system level top-down and bottom-up modelling will only be useful if their audience perceives the results to be relevant. Results of such analyses are increasingly applied to justify various decisions by different stakeholders such as policy-makers and consumers. As concluded by Williams et al. 2009, the future of LCA depends to a great extent on how the community decides to handle uncertainty. The same holds true for system level top-down and bottom-up modelling (Creutzig et al. 2012). Insufficient efforts puts public trust in the field at risk, and therefore transparency and handling of uncertainty related to methodological choices, parameters and modelling must be improved. Harmonisation of the practices and data management systems from goal and scope definition to interpretation phase should be systematically developed. Thus, conscious misuse of the LCA framework and system level modelling to warrant various decisions, and disinform public and private decision-makers can be avoided.

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Table A1. The annual production-based CO_2 emission intensity of electricity (g CO_2/kWh_e) in various OECD countries. The CO_2 emissions from combined heat and power production (CHP) allocated to power and heat on the basis of *the energy content of the products*. NA = data not available.

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008
Australia	970	964	1035	1068	1117	1100	1077	1094	1141	1118	1070
Austria	248	212	185	217	209	276	265	259	254	234	210
Belgium	372	392	330	316	312	313	324	317	304	293	293
Canada	236	212	258	268	254	259	239	227	216	243	210
Czech	867	892	808	790	740	668	662	655	653	697	674
Denmark	680	559	405	397	388	413	347	316	396	363	351
Finland	213	246	192	239	259	332	281	177	281	253	185
France	126	86	86	68	74	80	77	90	80	86	79
Germany	724	687	608	627	646	600	584	561	554	608	547
Greece	1240	1173	1012	1049	1004	966	972	976	900	923	899
Hungary	662	657	696	659	630	722	658	545	491	475	449
Iceland	0	2	0	0	0	0	0	0	0	1	1
Ireland	887	861	753	773	742	682	674	668	614	572	544
Italy	680	644	589	572	605	615	515	507	493	473	476
Japan	484	460	446	447	470	494	475	474	465	502	488
Korea	581	611	603	592	490	476	506	493	495	485	494
Luxembourg	NA	NA	NA	NA	437	429	398	408	419	416	420
Mexico	658	663	715	729	732	748	691	753	705	713	566
Netherlands	656	592	506	523	525	533	506	494	483	485	469
New Zealand	149	131	268	332	302	346	317	365	324	286	239
Norway	1	2	1	3	2	3	3	2	3	4	3
Poland	1071	1100	1011	998	999	997	988	984	926	936	902
Portugal	622	675	558	517	600	481	540	604	488	440	455
Slovak Republic	449	377	266	290	258	316	280	274	268	270	249
Spain	511	550	519	451	524	450	453	470	403	437	367
Sweden	11	16	14	15	20	26	20	18	20	15	15
Switzerland	13	14	15	14	14	14	15	17	16	15	15
Turkey	716	671	711	741	629	574	531	544	552	608	631
United Kingdom	813	631	560	574	555	578	578	574	598	589	572
United States	705	690	685	694	654	654	659	659	639	634	622
EU-27	560	510	462	457	466	465	444	438	433	446	417
OECD Total	579	553	543	550	537	537	531	531	521	528	507

Table A2. The annual production-based CO_2 emission intensity of electricity (g CO_2/kWh_e) in various countries. The CO_2 emissions from combined heat and power production (CHP) allocated fully to power (*the "motivation electricity" method*). NA = data not available.

	1990	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Australia	975	964	1035	1068	1117	1100	1077	1094	1141	1118	1070
Austria	305	270	229	268	256	331	321	311	314	288	262
Belgium	407	422	345	333	327	335	349	336	336	318	319
Canada	238	217	264	275	261	267	246	233	222	249	216
Czech	1209	1290	1070	1068	995	903	895	896	873	898	889
Denmark	1065	912	722	727	703	705	643	620	674	653	663
Finland	330	369	310	366	393	468	400	313	417	388	316
France	126	89	103	89	96	102	99	117	105	113	104
Germany	818	748	663	670	688	674	676	648	632	659	601
Greece	1240	1173	1018	1056	1011	976	981	987	912	931	908
Hungary	860	807	815	758	716	832	749	624	629	588	554
Iceland	0	2	0	0	0	0	0	0	0	1	1
Ireland	887	861	753	773	742	682	674	668	614	572	544
Italy	680	644	589	572	605	615	580	574	559	538	545
Japan	484	460	446	447	470	494	475	474	465	502	488
Korea	581	622	621	655	551	533	580	561	562	554	560
Luxembourg	NA	NA	NA	NA	475	478	440	459	471	463	477
Mexico	658	663	715	729	732	748	691	753	705	713	566
Netherlands	696	743	685	700	696	707	682	651	631	622	602
New Zealand	149	131	268	332	302	346	317	365	350	310	245
Norway	2	3	3	4	3	5	6	4	5	6	4
Poland	1819	1588	1389	1393	1385	1387	1372	1358	1268	1271	1229
Portugal	629	685	575	535	620	503	566	634	516	468	485
Slovak Republic	676	574	366	369	313	404	354	341	328	346	310
Spain	512	550	519	451	524	450	453	470	403	437	367
Sweden	40	61	51	51	66	79	66	57	65	52	53
Switzerland	25	26	26	25	26	27	28	32	31	28	28
Turkey	716	671	726	753	644	586	543	564	574	631	652
United Kingdom	813	631	560	574	555	578	578	574	598	589	572
United States	709	706	696	705	666	666	668	669	653	648	636
EU-27	672	593	526	520	527	533	519	512	504	510	481
OECD Total	612	585	572	579	566	571	565	563	554	558	536

Table A3. The annual consumption-based CO_2 emission intensity of electricity in OECD countries that trade electricity over the country borders (g CO_2/kWh_e). The CO_2 emissions from combined heat and power production (CHP) allocated to power and heat on the basis of *the energy content of the products*. NA = data not available.

	1990	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Austria	332	291	317	337	340	395	366	374	368	381	328
Belgium	374	377	310	268	288	297	313	311	291	287	294
Canada	256	220	272	283	267	279	258	244	236	258	230
Czech	899	894	823	810	773	726	715	718	698	732	696
Denmark	398	492	309	361	337	418	318	208	383	280	242
Finland	201	240	185	241	255	339	295	199	294	285	245
France	133	89	87	71	77	85	80	94	85	93	84
Germany	696	650	581	597	612	572	557	532	530	579	525
Greece	1223	1159	1004	1032	979	949	946	943	875	906	880
Hungary	719	647	572	550	511	588	559	466	448	424	419
Ireland	887	861	751	773	737	676	667	660	613	573	545
Italy	582	550	505	485	511	523	453	441	434	409	420
Luxembourg	NA	NA	NA	NA	569	525	522	512	451	507	486
Mexico	658	664	715	729	732	748	691	753	705	713	566
Netherlands	628	507	495	518	496	512	512	499	489	496	465
Norway	1	5	3	14	11	24	18	5	14	9	6
Poland	1017	1080	995	970	974	977	965	957	909	903	867
Portugal	613	664	553	511	590	477	523	576	473	440	435
Slovakia	489	445	428	434	426	487	454	448	446	541	433
Spain	508	532	500	439	505	440	444	460	396	429	362
Sweden	12	19	19	25	36	86	59	29	50	26	23
Switzerland	178	143	161	157	187	195	171	246	196	220	182
Turkey	714	671	707	734	628	575	534	546	554	610	632
United Kingdom	783	601	540	558	542	571	563	558	583	576	555
USA	701	683	679	689	650	651	655	654	634	629	616

Table A4. The annual consumption-based CO_2 emission intensity of electricity in OECD countries that trade electricity over the country borders (g CO_2/kWh_e). The CO_2 emissions from combined heat and power production (CHP) allocated fully to power (*the "motivation electricity" method*). NA = data not available.

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008
Austria	413	365	385	412	410	479	448	455	450	452	396
Belgium	408	412	332	282	311	326	346	341	330	320	330
Canada	258	225	278	290	274	286	265	250	243	264	237
Czech	1306	1292	1097	1101	1045	986	971	981	935	952	919
Denmark	630	803	549	616	573	661	552	405	616	487	444
Finland	347	394	324	409	428	536	472	381	479	456	412
France	133	92	105	91	99	107	102	120	110	119	109
Germany	789	714	641	647	661	649	653	625	612	635	585
Greece	1228	1166	1014	1047	995	969	967	967	898	927	903
Hungary	858	798	682	641	585	682	642	551	560	520	512
Ireland	887	861	751	773	737	676	667	660	613	573	545
Italy	584	551	509	489	516	528	513	502	494	468	484
Luxembourg	NA	NA	NA	NA	604	584	599	586	512	550	533
Mexico	658	664	715	729	732	748	691	753	705	713	566
Netherlands	669	636	641	664	637	660	668	637	617	614	577
Norway	2	10	7	27	21	44	36	10	26	16	11
Poland	1688	1548	1362	1353	1348	1356	1336	1320	1243	1218	1174
Portugal	621	672	569	527	608	496	544	600	495	462	458
Slovakia	656	646	581	571	552	648	602	592	581	705	564
Spain	509	533	502	440	506	441	445	461	397	429	363
Sweden	39	63	56	67	88	161	119	71	107	67	65
Switzerland	203	163	184	178	210	227	206	293	234	251	213
Turkey	715	671	726	752	648	589	546	567	577	633	653
United Kingdom	783	601	540	558	542	571	564	559	584	577	556
USA	705	699	690	700	662	663	664	664	649	643	629

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Title	**Assessing the uncertainties of climate policies and mitigation measures** **Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments**
Author(s)	Sampo Soimakallio
Abstract	Ambitious climate change mitigation requires the implementation of effective and equitable climate policy and GHG emission reduction measures. The objective of this study was to explore the significance of the uncertainties related to GHG emission reduction measures and policies by providing viewpoints on biofuels production, grid electricity consumption and differentiation of emission reduction commitments between countries and country groups. Life cycle assessment (LCA) and macro-level scenario analysis through top-down and bottom-up modelling and cost-effectiveness analysis (CEA) were used as methods. The uncertainties were propagated in a statistical way through parameter variation, scenario analysis and stochastic modelling. This study showed that, in determining GHG emissions at product or process level, there are significant uncertainties due to parameters such as nitrous oxide emissions from soil, soil carbon changes and emissions from electricity production; and due to methodological choices related to the spatial and temporal system boundary setting and selection of allocation methods. Furthermore, the uncertainties due to modelling may be of central importance. For example, when accounting for biomass-based carbon emissions to and sequestration from the atmosphere, consideration of the temporal dimension is critical. The outcomes in differentiation of GHG emission reduction commitments between countries and country groups are critically influenced by the quality of data and criteria applied. In both LCA and effort sharing, the major issues are equitable attribution of emissions and emission allowances on the one hand and capturing consequences of measures and policies on the other. As LCA and system level top-down and bottom-up modelling results are increasingly used to justify various decisions by different stakeholders such as policy-makers and consumers, harmonization of practices, transparency and the handling of uncertainties related to methodological choices, parameters and modelling must be improved in order to avoid conscious misuse and unintentional misunderstanding.
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Nimeke	**Ilmastopolitiikkatoimien ja päästövähennysten epävarmuuksien arviointi** **Näkemyksiä biopolttoaineiden tuotannosta, verkkosähkön kulutuksesta ja päästövähennysvelvoitteiden taakanjaosta**
Tekijä(t)	Sampo Soimakallio
Tiivistelmä	Kunnianhimoiset tavoitteet ilmastonmuutoksen hillitsemiseksi edellyttävät tehokkaiden ja oikeudenmukaisten ilmastopolitiikka- ja päästövähennystoimenpiteiden toteuttamista. Tämän tutkimuksen tavoitteena oli analysoida kasvihuonekaasupäästöjen vähentämiseen liittyvien keinojen ja politiikkatoimenpiteiden epävarmuuksia tarkastelemalla biopolttoaineiden tuotantoa ja verkkosähkön kulutusta sekä päästövähennysvelvoitteiden taakanjakoa maiden ja maaryhmien välillä. Menetelminä käytettiin elinkaariarviointia, makrotaloustason skenaarioanalyysia ja kustannustehokkuusanalyysia. Epävarmuuksia tarkasteltiin tilastollisten menetelmien avulla mm. parametrien oletuksia vaihtelemalla, skenaarioanalyysilla ja stokastisella mallintamisella. Tulokset osoittavat, että tuote- tai prosessitasolla biopolttoaineiden tuotannon ja verkkosähkön kulutuksen kasvihuonekaasupäästöihin liittyy merkittäviä epävarmuuksia, joita aiheutuu arvioinnissa käytettävistä parametrioletuksista, esimerkiksi maaperän typpioksiduulipäästöille ja hiilivaraston muutoksille sekä sähköntuotannon päästöille. Epävarmuuksia aiheutuu myös tarkastelujen rajauksista ja allokointikäytännöistä sekä mallinnukseen liittyvistä tekijöistä, kuten biomassan hiilen vapautumisen ja sitoutumisen välisen ajallisen esiintymisen käsittelemisestä. Maa- tai maaryhmätasolla päästövähennysvelvoitteiden taakanjaossa sovellettavat kriteerit ja tietopohja ovat kriittisiä tulosten kannalta. Sekä elinkaariarvioinnissa että taakanjaossa päästöjen ja päästövähennysvelvoitteiden oikeudenmukainen kohdentaminen ja kerrannaisvaikutusten arvioiminen ovat keskeisiä tekijöitä ja voivat edellyttää useiden erilaisten menetelmien käyttämistä. Elinkaariarvioinnin ja järjestelmätason mallinnuksen tuloksia käytetään enenevässä määrin erilaisten päätösten perusteena. Tarkoitushakuisen väärinkäytön ja tarkoituksettomien väärinymmärrysten välttämiseksi on erittäin tärkeää, että elinkaariarviointiin ja järjestelmätason mallinnukseen liittyviä käytäntöjä yhtenäistetään, tulosten ja oletusten läpinäkyvyyttä lisätään ja menetelmiin, parametreihin ja mallinnukseen liittyvien epävarmuuksien käsittelyä parannetaan.
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Assessing the uncertainties of climate policies and mitigation measures

Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments

Climate change is the major, primarily environmental issue of our time, and the single greatest challenge facing environmental regulators. Anthropogenic greenhouse gas emissions have increased significantly from the pre-industrial times. The consumption of primary energy has doubled since the early 1970s, and electricity consumption has increased almost fourfold. Ambitious climate change mitigation requires rapid and extensive measures, especially in energy production and consumption, enabling deep cuts in the GHG emissions within the upcoming centuries.

By the end of 2011, the viewpoints of the major emitters concerning binding GHG emission reduction targets and effort sharing between countries, have been too diverge for a breakthrough in international climate negotiations. However, various climate policies are implemented actively, in particular in the European Union. The use of renewable energy sources and transportation biofuels are promoted with mandatory commitments. At the same time, the environmental performance of product systems, over the life cycle from cradle to grave, is being increasingly assessed to justify various decisions.

Differentiation of emission reduction commitments between countries is a value-based issue. The implications of effort sharing may strongly depend on the criteria applied. When assessing GHG emission performance of product systems, a number of assumptions are required. This dissertation explores the significance of uncertainties related to GHG emission reduction policies and measures. Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments are provided.

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