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Environmental Input-Output Assessment of Integrated Second Generation Biofuel Production in Fenno-Scandinavia

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Master of Science in Energy and Environment
Submission date: July 2009
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Problem Description

The primary objective of the thesis work will be to assess the environmental impacts associated with the integrated production and use of second generation biofuels produced from boreal forests feedstocks within the Fenno-Scandinavian region. The integrated IO-LCA framework will be applied for the analysis. This will be first entail an assessment of both the current and future boreal forest-derived resource potential throughout the entire Fenno-Scandinavian region suitable for use in biofuel production, followed by an assessment of the regional potential for integrated production with existing pulp and paper industries. This will be succeeded by unit-level impact analysis of the selected systems. Additional analysis of factor use and environmental performance trade-offs of the various systems should be included.

The second objective is to apply the integrated IO-LCA framework to perform integrated biofuel production and consumption scenario analyses for Fenno-Scandinavia. The scenarios will address the utilization of a specific national or regional resource bade through the set of selected integrated biofuel production systems. Systems selected for use in scenario analysis will be determined over the course of the semester through ongoing discussions with the academic supervisor(s). The scenarios will be based on projections of future regional and national final demand of goods, services and land-based transport energy in light of the competition for use of the resource base in other product and/or energy systems. The student should keep in mind all dimensions of sustainable development in the final discussion.

Assignment given: 16. February 2009
Supervisor: Anders Hammer Strømman, EPT

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MASTER THESIS

for

Thomas Gibon
Spring 2009

Environmental Input-output Assessment of Integrated Second Generation Biofuel Production and Consumption Scenarios in Fenno-Scandinavia

Miljøevaluering av scenario for integrert produksjon og konsum av andregenerasjons biodrivstoff i Fenno-Skandinavia

Background

Biofuels – particularly so-called "2nd Generations" – have the significant potential to both mitigate climate change and ease the transition to a less fossil-dependent transport sector (IEA 2004; IEA 2008; Renewable Fuels Agency 2008; Ribeiro *et al.* 2007). Significant advancements in process design in recent years will result in the deployment of the first commercial 2nd generation biofuel plants by 2012 (OECD 2008). Yet, of over 60 reports on the environmental profile and production potential of biofuels worldwide that were recently reviewed by the OECD, less than 20 studies had investigated "2nd Generations" (OECD 2008). Thus, there is a need to add to the limited body of knowledge surrounding the environmental implications of advanced biofuel production systems and technologies which are under intensive research and development today, particularly in a Scandinavian context.

Additionally, many of the afformentioned studies of the environmental impacts of biofuels focused on systems utilizing stand alone biofuel production processes and technologies. Within Scandinavia, there exists significant potential for synergetic production of advanced biofuels with other industries, particularly the pulp and paper industry, which may provide opportunities for producing multiple value-added co-products in tangency with liquid fuel while capitalizing on improved process efficiencies. Moreover, the pulp and paper industry has a highly efficient infrastructure for growth, harvesting, transport, and processing of forest materials, making the industry an ideal candidate for efficient biofuel production across the complete value chain (Holladay *et al.* 2007).

It is growing increasingly important that future biofuel systems based on 2nd Generation technologies are assessed *before* their rapid and large-scale deployment, unlike the diffusion of today's crop-based agro-fuels – of which many carry negative unforeseen environmental and social impacts which are linked to their production. This ensures that sound investments are directed towards those technologies and system designs that are expedient in terms of mitigating global warming and sustainable development in general.

Life cycle assessment (LCA) is the prevailing method for holistic environmental analysis, and is the recommended framework by the European Commission for use when assessing environmental impacts of biofuels (Ribeiro *et al.* 2007; Gnansounou *et al.* 2007; Johnson and Roman 2008; Edwards *et al.* 2007; European Commission 2008). However, some of the more recent criticism concerning LCA of biofuels stems from the difficulties in accounting for emission leakage that may occur outside the boundary of the focal biofuel production system. This has lead to an expanded awareness that the scope and system boundary of LCA-type studies should be extended, and that modified LCA models and frameworks which allow for such an extension of a system's boundaries to include multiple regions, economies, and systems may be better suited to do so. Multi-region hybrid LCA is the emerging framework suitable for such analyses.

Objective

The primary objective of the thesis work will be to assess the environmental impacts associated with the integrated production and use of 2nd generation biofuels produced from boreal forests feedstocks within the Fenno-Scandinavian region. The Integrated IO-LCA framework will be applied for the analysis. This will first entail an assessment of both the current and future boreal-forest derived resource potential throughout the entire Fenno-Scandinavian region suitable for use in biofuel production, followed by an assessment of the regional potential for integrated production with existing pulp and paper industries. This will be succeeded by unit-level impact analysis of the selected systems. Additional analysis of factor use and environmental performance tradeoffs of the various systems should be included.

The second objective is to apply the integrated IO-LCA framework to perform integrated biofuel production and consumption scenario analyses for Fenno-Scandinavia. The scenarios will address the utilization of a specific national or regional resource base through the set of selected integrated biofuel production systems. Systems selected for use in scenario analysis will be determined over the course of the semester though ongoing discussions with the academic supervisor/s. The scenarios will be based on projections of future regional and national final demand of goods, services, and land-based transport energy in light of the competition for use of the resource base in other product and/or energy systems. The student should keep in mind all dimensions of sustainable development in the final discussion.

The analysis should include following elements:

1) Resource assessment of the existing boreal forest resource base within Fenno-Scandinavia.
2) Assessment of the potential for integrated biofuel production with existing industry across the Fenno-Scandinavian region.
3) Compilation and hybridization of feedstock production life cycle inventories.
4) Compilation and hybridization of integrated biofuel production life cycle inventories (Fenno-Scandinavia).
5) Development of a basic MRIO database.
6) Unit-level LCIA using integrated IO-LCA.
7) Scenario analysis using an MRIO framework .

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Within 14 days of receiving the written text on the diploma thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to complete a well presented report. In order to ease the evaluation of the thesis, it is important that the cross references are correct. In the making of the report, strong emphasis should b e placed on both a thorough discussion of the results and an orderly presentation.

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Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering, 12. January 2009

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Environmental Input-Output Assessment of Integrated Second Generation Biofuel Production in Fenno-Scandinavia

Miljøevaluering av scenario for integrert produksjon av andregenerasjons biodrivstoff i Fenno-Skandinavia

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Faculty of Engineering Science and Technology
Department of Energy and Process Engineering
Industrial Ecology Programme

Master Thesis

10th July 2009

Foreword

This report was written in order to meet the requirements for the obtaining of my M. Sc. at the Norwegian University of Science and Technology (NTNU). This was done within the Industrial Ecology Programme, Department of Energy and Process Engineering.

I would like to thank all the persons who participated, directly or indirectly, to this project. This includes, in first place, my supervisor, Anders Hammer Strømman, as well as my co-advisor, Ryan Bright, for their precious help and guidance all along this semester. I am also grateful to Troy Hawkins, who was always ready to listen to my questions, Richard Wood and his extensive knowledge of Matlab as well as Raquel Santos Jorge and Anders Arvesen who helped to compile the model.

Further acknowledgements go to my fellow students, Åsa, Børge, Kjartan and Stian, for the rich discussions that we have had over the past year and the common work we have made together (i.e. chapters 2 and 3). I would like to express my gratitude to all the people at the department of Industrial Ecology for all the nice moments we shared together. Last but not least, Mari and Chris: thank you so much for revising my awkward written English and making this paper surely more intelligible!

Thomas Gibon,
Trondheim, July 2009.

Abstract

The goal of this study is to investigate the potential implementation of integrated dimethyl ether (DME) production from by-products of the pulp and paper industry in Fenno-Scandinavia (Finland, Norway and Sweden) and to quantify the consequences of several use scenarios in which fossil fuels were gradually substituted by DME.

To that end, two analytical frameworks were jointly used, life cycle assessment (LCA) and environmentally-extended input-output analysis (EEIOA). The first framework was utilised to make an exhaustive inventory of the Chemrec ® (Lindblom & Landälv, 2007) process and its integration in the Finnish, Norwegian and Swedish contexts. The latter framework was employed in order to incorporate this production system into a multi-regional (actually *global*) input-output model that has been created for the purpose of the study. For data availability reasons, the stressors that have been examined are anthropogenic carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O), widely regarded as the elements which are responsible for the most serious environmental impacts. Three different story lines (plus a baseline scenario) were taken into account: a resource assessment scenario, in which a total implementation is assumed; a policy-independent approach setting a constant increase in the use of biofuels and a policy-compliance approach, aiming at satisfying European directive goals. It results that 5.21 to 20.6 Mt of DME can be produced, while the range of greenhouse gases emissions that can be saved thanks to a black liquor-based DME production scheme goes from 46.7 (scenario 3) to 70.5 (scenario 2) Mt in 2050, that is, 8.15–12.8% out of the otherwise total emissions in Fenno-Scandinavia.

This LCA/IO analysis emphasises that the amount of greenhouse gases emissions embodied in every kg of DME highly depends on each country's background economy and evolves considerably along the decade, unit-level analysis show drastic reductions (-15% to -57% between 2000 and 2050) in DME embodied emissions. A nationwide analysis highlights a very important potential from the Finnish pulp and paper industry. All in all, it shows that such a biofuel production scheme should be implemented in countries that have an remarkable environmental profile to obtain very significant environmental performances. Only a joint effort of all the key sectors (energy, transportation, households) can lead to climate change mitigation and energy security.

Sammendrag

Målet med denne studien er å undersøke potensialet for implementering av integrert dimetyleter-produksjon fra biprodukter ("black liquor") av papirindustrien i Fenno-Skandinavia (Finland, Norge og Sverige) og å kvantifisere konsekvensene av flere forbruksscenarioer der fossilt brensel gradvis blir erstattet av DME.

For å nå dette målet, ble to analytiske rammeverk brukt sammen, livssyklusanalyse (LCA) og input-output-analyse, for å modellere verdikjeden til et slikt produkt. Den første rammen ble utnyttet til å lage et utfyllende inventar av Chemrecprosessen (Lindblom & Landälv, 2007) og dens integrering i finske, norske og svenske kontekster. Den sistnevnte rammen ble brukt for å innlemme dette produksjonssystemet i en multiregional input-output-modell som har blitt opprettet for studiens formål. Begge teknikkene har argumenter for og imot, men såkalt *hybridisering* muliggjør en mer nøyaktig modellering. Av datatilgjengelighetsgrunner, var de undersøkte substansene menneskeskapt karbondioksid (CO_2), metan (CH_4) og dinitrogenmonoksid (N_2O), allment betraktet som de elementene som er ansvarlige for de mest alvorlige miljøvirkningene. Tre forskjellige scenarioer (pluss ett baseline scenario) ble tatt hensyn til: ett cellulose- og papirkoplingsscenario som setter raffinert DME proporsjonalt til cellulose- og papirindustriproduksjon; ett hvor mengden biodrivstoff produsert blir bestemt og ett med sikte på å nå CO_2-politiske mål. Det resulterte i 5,21 til 20,6 Mt DME som kan produseres, mens omfanget av klimagassutslipp som kan lagres takket være den "black liquor"-baserte DME-produksjonsordningen, går fra 46,7 (scenario 3) til 70,5 (scenario 2) Mt i 2050. Dette tilsvarer 8,15–12,8% av de totale utslippene i Fenno-Skandinavia som skapes ellers.

Denne LCA / IO-analysen understreker at mengden klimagassutslipp som utformes for hvert kg av DME er svært avhengig av hvert lands nasjonale bakgrunnsøkonomi og utvikler seg betraktelig gjennom tiårene. Den finske papirindustrien har ogs et stort potensiale. Alt i alt, viser det at en slik biodrivstoffproduksjonsordning bør gjennomføres i land som har en aktiv miljøprofil for å få svært signifikante miljømessige ytelser. Bare en felles innsats av alle nøkkelsektorer (energi, transport, husholdninger) kan fre til reduserte klimaendringer og å garantere energisikkerhet.

Résumé

Le but de cette étude est d'examiner la mise en place de la production intégrée d'éther méthylique (DME) obtenu à partir d'un dérivé de l'industrie papetière (appelé « liqueur noire ») en Fenno-Scandinavie (Finlande, Norvège et Suède) et de mesurer les conséquences de différents scénarios simulant un remplacement progressif des carburants fossiles par cet agrocarburant.

Pour ce faire, deux outils de modélisation ont été utilisés de manière conjointe, l'Analyse du Cycle de Vie (ACV) et l'Analyse Entrée-Sortie. Le premier a servi à élaborer un inventaire exhaustif du procédé Chemrec ® (Lindblom & Landälv, 2007) et son intégration dans les différents contextes finlandais, norvégien et suédois. Le recours à la seconde méthode a permis d'incorporer ce système dans un modèle d'entrée-sortie multirégional (*mondial*) qui a été développé exclusivement pour cette étude. Le principal impact étudié sera le potentiel de réchauffement climatique dû aux émissions de dioxyde de carbone (CO_2) anthropique, de méthane (CH_4) et de protoxyde d'azote (N_2O), reconnus comme les gaz à effet de serre les plus puissants. Trois différents cas (en plus d'un cas de référence) ont été modélisés : un scénario dont le but est de connaître le volume théorique maximale de DME pouvant être produit ; une approche fixant la quantité d'agrocarburant produite selon des critères réalistes et une troisième approche visant à atteindre les seuils d'émissions de gaz à effet de serre prescrits par la législation. Il résulte qu'entre 5,21 et 20,6 Mt de DME pourraient être produits annuellement pour la décennie 2040–2050. Le spectre de valeurs de quantités de CO_2 pouvant être économisées accompagnant cette production s'étend de 46,7 à 70,5 Mt d'équivalent CO_2 par an à l'horizon 2050, soit 8.15–12.8% des émissions totales en Fenno-Scandinavie.

Cette analyse hybride ACV/Entrée-Sortie met en exergue la dépendance entre le bilan carbone d'un kilogramme de DME et le profil environnemental du pays dans lequel cet agrocarburant serait produit. Les résultats montrent que plus l'industrie de la région concernée est « verte », plus l'empreinte écologique du DME produit à partir de liqueur noire serait réduite, et ce de manière drastique (de -15% à-57% entre 2000 et 2050). Plus généralement, il n'y a pas *un* remède miracle aux problèmes d'effet de serre, seule une mobilisation importante de tous les secteurs-clés de l'industrie peut venir à bout du réchauffement climatique ainsi que de notre dépendance aux énergies fossiles.

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Nomenclature

Table 1: Abbreviations, acronyms and chemical symbols used in this report.

Acronym	Definition
ACV	Analyse du cycle de vie (LCA)
ADP	Abiotic Depletion Potential
AP	Acidification Potential
BLGCC	Black Liquor Gasification Combined Cycle
BLGMF	Black Liquor Gasification for Motor Fuels
BtL	Biomass-to-Liquid
CFCs	Chlorofluorocarbons
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DM	Dry Matter
DME	Dimethyl Ether
EEIO(A)	Environmentally-Extended Input-Output (Analysis)
EJ	Exajoule ($= 1 \times 10^{18} J$)
EP	Eutrophication Potential
ESA	European System of Accounts
ETBE	Ethyl-tertiary-butyl ether
EU23	cf. 3.1.1
Eurostat	Statistical Office of the European Commission
FAETP	Fresh Aquatic Eco-Toxicity Potential
FI	Finland
FT	Fischer-Tropsch
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GJ	Gigajoule ($= 1 \times 10^{9} J$)
Gt	Gigatonne ($= 1 \times 10^{9} t$, metric)
GTAP	Global Trade Analysis Project
GWP	Global Warming Potential

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HDS	Hydrodesulfurisation
IO(A)	Input-Output (Analysis)
IPCC	Intergovernmental Panel for Climate Change
ISO	International Organisation for Standardisation
JRC	(European Commission) Joint Research Centre
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LPG	Liquid Petroleum Gas
Mg	Megagramme $(= 1 \times 10^6 g)$
Mt	Megatonne $(= 1 \times 10^6 t$, metric)
MTBE	Methyl-tertiary-butyl ether
MW	Megawatt $(= 1 \times 10^6 J/s)$
MW_i	Molar Weight of element i
N	Nitrogen
NACE	Nomenclature statistique des Activités économiques dans la Communauté Européenne (Statistical Classification of Economic Activities in the European Community)
N_2O	Dinitrogen monoxide (commonly “nitrous oxide”)
NAMEA	National Accounting Matrix including Environmental Accounts
NEC	Non elsewhere classified
NO	Norway
NTNU	Norges teknisk-naturvitenskapelige universitet (Norwegian University of Science and Technology)
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Co-operation and Development
ORC	Organic Rankine Cycle
P	Phosphorous
PJ	Petajoule $(= 1 \times 10^{15} J)$
PO_4^{3-}	Phosphate ion
POCP	Photochemical Ozone Creation Potential
RENEW	Renewable Fuels for advanced Powertrains Workgroup
RME	Rape Methyl Ester
RoW	Rest of the World
SE	Sweden
SME	Soybean Methyl Ester
SO_2	Sulfur dioxide
toe	Tons of oil equivalent (= 41.868 GJ $= 41.868 \times 10^9 J$)
TTW	Tank-to-Wheel

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UNECE	United Nations Economic Commission for Europe
WTT	Well-to-Tank
WTW	Well-to-Wheel

Chapter 1

Introduction

Renewable sources of energy have become a major topic that decision-makers address with more and more concern, with regard to climate change and energy security policies. There exists an indisputable anthropogenic effect on greenhouse gases emissions, and it has actually been so since the beginning of Industrial Age. We now enter an era in which an enormous share of the people living in developed countries are becoming conscious on their own impact on the environment, so-called individual "carbon footprint", which has to be seriously mitigated in a near future. Clearly mentioned by Meadows, Randers and Meadows (2004), this multi-parameter issue can be expressed as such:

$$I = P \times A \times T \tag{1.1}$$

where I standing for impact, as "ecological footprint" is directly depending on three other crucial factors: the population P whose live standards are given by the affluence A, assuming an efficiency of technology T (Meadows *et al.*, 2004). The most flexible parameter we can play with is the technology factor. Furthermore, since anthropogenic activities rely more and more on technology, this parameter is crucial. This is true for sectors like transportation, in which efficiency is always prone to improvements. However, the demand for transportation fuels in Europe has increased by 35% for freight and 20% for passenger transport from 1995 to 2006 (the European Commission, 2009), which is higher than the better expectations about energy efficiency improvements.

1.1 Motivation

On 23 January 2008, the European Commission published an ambitious and thorough paper, a package of proposals that aim at being guidelines for the upcoming years in terms of energy security, environmental policies and greenhouse gas cut-offs. In December the same year, the European Parliament and Council agreed on adopting this package. The goals are simple but far-reaching: 20% more renewable sources in the energy mix and 20% less greenhouse gases emitted by 2020. This illustrates well the recent willingness of policy-makers to tackle the climate change issues, which is today undeniably a central concern for everyone. Analogously, the research activities in this domain has been more and more intense during the last years, highlighting potential and sustainable solutions such as wind, solar or biomass as sources for the production of an energy which becomes more and more precious every day.

Between 1970 and 2004, global emissions of greenhouse gases have soared: from 28.7 to 49 Gt CO_2 equivalents, a 70% increase (Barker *et al.*, 2007). According to the United Nations (2009a) 24.2 Gt of carbon dioxide were released in 2000 worldwide, while 18.6 Gt were emitted in 1980, a 30% increase. In the meanwhile, world energy consumption has raised from 298.8 EJ to 419.8 EJ, a 40% increase (the Energy Information Administration, 2006). There is an unquestionable dependence between energy demand and greenhouse gases emissions. The main challenge is then to decouple these two variables, and allow the anthroposphere to maintain a reasonable level of activities while exploiting less natural resources and releasing less waste and emissions. This is actually one of the most important issues of industrial ecology, so-called *dematerialisation*. Regarding transportation, some additional challenges have to be addressed: a substitute to fossil fuel should be an energy carrier with a high heating value, with physical and chemical properties that make it realistically usable with current technology, or at least without very substantial modifications. Parallel to the decision-making processes, the amount of projects and feasibility studies has rocketed in the field of biofuels.

Among these studies, a very few of them address recovering of by-products as a basis for biofuel production. This is the case for Ekbom *et al.* (2005); Lindblom & Landälv (2007) who analyse the potential of DME production from a by-product of the pulp and paper industry, the so-called "black liquor". The pulp and paper industry is a top actor in the European economic context: in 2002, the 10 most important forest and paper products companies generated a total turnover of € 60.8 billion. At the same time, the role of Scandinavian pulp and paper industry is considerable at a global scale. In this connection, *Stora Enso*, a Fenno-Swedish-owned company, was the second most important pulp and paper firm in the world in 2007, in terms of net sales (PricewaterhouseCoopers, 2008). Szabó *et al.* (2009) have explored the implications of a climate change commitment scenario in the pulp and paper industry. They have shown that the use of black liquor for heat generation is central regarding greenhouse gases emission mitigation. As of 2009, every pulp mill internally reuses black liquor, with a low energy efficiency, for heating. There is an enormous opportunity to seize: increase this energy efficiency by gasifying black liquor and producing high-grade DME from it.

The choice of black liquor as feedstock is justified by 3 main advantages over alternative biomass sources, namely (Ekbom *et al.*, 2006) (1) integration to pulp and paper mills allows simplified handling operations (2) easiness of pressurisation enhances efficiency and (3) gasification capital cost is shared between the recovery of organic chemicals, steam production and syngas production. (Joelsson &

Gustavsson, 2007)

1.2 State of the field

Regarding the increasing interest and the many ongoing discussions about biofuel production, many studies have been provided recently. Quite early, Lienhard & Bierbach (1986) published a study called "Gasification of biomass and its application in the pulp and paper industry" about gasification of wood, using a circulating fluidised bed gasification pilot plant in a pulp mill. Integrating biorefineries to pulp and paper mills was then already a topical issue. Later on, Pindoria *et al.* (1997) assessed the efficiency of two distinct processes, pyrolysis and gasification. They based their analyses on data obtained with Eucalyptus, considered as a short-rotation coppice species. They concluded that pyrolysis gives better results than gasification in terms of efficiency, although this efficiency is hardly technically improvable. However, it does not apply to integrated production. Several other reviews of existing technologies were published afterwards (Hamelinck & Faaij, 2006; Kim & Dale, 2005; McKendry, 2001; Zabaniotou *et al.*, 2007; Zinoviev *et al.*, 2007).

JRC, EUCAR & Concawe (2007) provide a very comprehensive LCA study about a very wide panel of fuels: conventional fuels, such as gasoline and diesel; compressed natural gas; biogas; liquefied petrol gas; "conventional" biofuels, such as ethanol and biodiesel; methyl- and ethyl-tertiary-butyl ether (MTBE/ETBE); synthetic diesel fuel; dimethyl ether (DME) and hydrogen. This report addresses DME from black liquor gasification, it is highlighted as a (almost) carbon-neutral fuel, from a well-to-wheel point of view. Some general key findings from this study are relevant and crucial: "a WTW analysis is the essential basis to assess the impact of future fuel and powertrain options", "results must further be evaluated in the context of volume potential, feasibility, practicability, costs and customer acceptance of the pathways investigated", "a shift to renewable/low fossil carbon routes may offer a significant GHG reduction potential but generally requires more energy". The same type of conclusions can be yielded when it comes to other second generation biofuel, e.g. biomass-to-liquid fuels (Gibon, 2008) which show trade off patterns between eutrophication and global warming potentials. *Ergo*: the authors have raised the importance of methodology but also the necessary investigation of other impacts than greenhouse gases emissions.

The key findings of the majority of studies about biofuel production are (non exhaustively):

1. to focus only on global warming potential must be justified,

2. the use of biofuels is not *exactly* carbon-free, but the amount of carbon dioxide which is released during this phase might be accounted as "biogenic", supposedly equal to the biomass feedstock CO_2 uptake throughout its growth, consequently

3. one should be careful when it comes to assessing flows that are difficult to measure (i.e. take into account uncertainties),
4. another effect is hard to quantify: direct and indirect land use change (although less relevant for forest management),
5. beyond the question of environmental impacts, other trade off phenomena can occur (mainly addressing social and economic concerns),
6. biofuels cannot ensure the whole energy supply in most countries, for various reasons but can be part of a larger "environmentally-friendly package" of solutions that can lead to dematerialisation, the Graal of industrial ecologists.

The potential of forests is very promising, especially in Scandinavian countries. Bright (2008) has analysed the feasibility and assessed the impacts of wood-based production in Norway. Based on different consumption scenarios (business-as-usual, passive, aggressive) and utilising hybrid LCA/IO analysis, very interesting issues were raised, namely concerning the resource competition with pulp and paper industry. Investigated feedstocks were residues from sawing industries and forestry. A positive conclusion states that enough renewable resources are available to implement a local fuel production scheme in Middle Norway, based on wood. Furthermore, the author corroborates findings from a study by Statens forurensningstilsyn (2007), Norwegian CO_2 mitigation potential is approximately 1.4 Mt by 2020, in the case of a 20% displacement of fossil fuels for land transportation and other motor fuel usage.

Recent studies have shown the high potential of woody biomass-based biofuels, especially in Scandinavian countries. One of them, a paper by Gustavsson *et al.* (2007), presents a thorough panel of processes compared to their fossil equivalent technology. Results are definitely highlighting the benefits of using wood-based biofuels, especially concerning transportation fuels: from 219 (for DME) to 411 (ethanol) PJ of automotive fuel can be produced out of Swedish forests. The same products are respectively associated with 102.4 and 76.1 GJ of biomass per Mg of carbon avoided (or PJ of biomass per Mt of avoided carbon emissions). When one notices that, in 2000, any Scandinavian country barely reached 50 Mt of CO_2 emissions (although one kilogramme of "carbon" is not equivalent to one kilogramme of CO_2), that is a proof biofuels can be one of the solutions to cut rocketing greenhouse gases emissions. Another key finding of the study is the gap between the performances of four transportation biofuels (ethanol, methanol, DME and FT-diesel) and the rest of wood-based fuels: the former show savings both on environmental and economical fields, whereas the latter show trade-off between these two criteria. In other words, aiming at fulfilling one objective only can diminish the possibility of achieving a parallel goal. These trade-off issues actually concern a lot of parameters, which are more or less closely related to the final product itself. A serious potential trade-off problem occurs at the right beginning of the value chain: it has been proved that land use change can have substantial effects on carbon stock changes. Bird *et al.* (2008) have written that "the emissions caused by the loss of carbon stocks should be considered". Analogously, it is possible to find statistics about greenhouse gases emissions in Sweden that take into account land use change on Statistiska Centralbyrån (2009) web pages: these can easily reach more than 10 Mt of CO_2 per year.

If DME does not seem to offer the best economico-environmental performances (Gustavsson *et al.*, 2007), it is important to notice that it can already be technologically supported by LPG-fuelled cars, as stated by the European Project BioDME (2008). LPG and DME indeed have similar characteristics regarding their state at standard conditions, with boiling points of -30°C and -25°C respectively they are both gases[1]. The implementation of a distribution and use pattern is consequently very easy to organise, as the whole infrastructure that is dedicated to LPG today is potentially utilisable for DME. Further interesting points about DME are to be developed in section 4.2. Concerning current BLGMF (black liquor gasification for motor fuels) technologies, they are still considered as "state-of-the-art" (Renew Project Group, 2008). Although technology has evolved considerably since the 1960s (Bergholm, 1963), the first demonstration plant was indeed built in 1987. However, the authors of the Renew Final Report estimate that, at current plant construction pace, 25% of Swedish pulp and paper plants will be equipped with such biorefineries in 2020. This technology is, yet in an early development phase, very promising.

Due to the numerous possible pathways that technology can offer and which can lead to a more environmentally-friendly and fossil-independent future, it is crucial to investigate all the aspects of each technological solution, with regard to the context in which it can be used. It is an accepted fact that dimethyl ether is seen as a promising biofuel. DME is potentially produced from by-products from pulp and paper industry, which is unquestionably well-implemented in Fenno-Scandinavia. In the light of current and upcoming policy guidelines as well as methodological tools such as life cycle assessment and input-output analysis, the present study aims at answering the following question:

> To what extent can integrated biofuel production in Fenno-Scandinavia be a solution *both* to fossil resource depletion and increasing global warming anthropological impact?

1.3 Strategy

This report first includes a chapter about the different methods that have been used for the study, from a theoretical point of view to a technical application to the presented cases. The details of the multi-regional model that has been constructed on purpose for this study are covered by chapter 3. This part is followed by a comprehensive presentation of the investigated technology, as well as the various

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[1] `http://www.biodme.eu/dme_as_a_fuel.html`

scenarios that are to be explored, in chapter 4. Subsequently, results to the study are being shown in chapter 5. Finally a discussion chapter (6) will conclude the thesis, with the objective of connecting the results to other literature and policy background.

Chapter 2

Input-output analysis and environmental extensions

Two main frameworks have been used for this study, life cycle assessment (LCA) and, to a much higher extent, environmentally-extended input-output analysis (EEIOA). While the first method is generally accepted as one of the best tools for a wide range of processes and products, the latter is considered as more comprehensive, including, *inter alia*, a "systematically complete system boundary" (Crawford, 2007). A proper combination (*hybridisation*) of both methods leads to a framework where methods weaknesses are covered by the other's strengths. In this chapter, the emphasis has been put on input-output, which actually shares its main principles with LCA. This chapter is the fruit of a collaborative writing work together with four fellow students: Åsa Grytli Tveten, Stian Rein Andresen, Børge Andreas Johansen and Kjartan Steen-Olsen. In this chapter and the rest of the paper, capital letters denote matrices while lower case characters represent scalars or vectors (one-row or one-column matrices). NB: there is an exception for the net final demand, which can be represented by a matrix or a vector, depending on how consumption sectors are aggregated. It will always be denoted y.

2.1 Presentation

The name *input-output analysis* refers to an analytical framework which uses matrices to model the economy of a country or a region. Professor Wassily Leontief, a 1973 Nobel Prize laureate, is unanimously credited with the development of this powerful tool (Leontief, 1970). The main interest of this framework relies on the possibility to model the flows from all economical sectors to every other sector of a given region. The input-output methodology is based on a set of matrices representing total flows (Z), technology (A) as well as an exogenous final demand (y) resulting in a total output (x). Researchers quickly realised the potential of this framework when applied to environmental issues. Environmentally extended IOA uses a stressor and a characterisation matrices to connect economical flows to environmental impacts. Nonetheless, IOA has specific features, including an additional value added vector. Most of this section is adapted from notes and material from the input-output analysis course at NTNU (Strømman, 2008).

Input-output tables are derived from supply and use tables (SUT) that are part of a well-known framework that is usually utilised for nationwide bookkeeping activities: the SNA (System of National Accounts) integrated national accounting structure. The supply and use framework distinguishes industries, sectors and products through double entry bookkeeping models. According to the type of classification (*ISIC*: International Standard of Industry Classification, *NAICS*: North American Industry Classification System, *NACE*, referring to French: Nomenclature des Activités économiques dans la Communauté Européenne. . .), aggregation can generate a wide range of detail levels, typically from 40 × 40 up to 500 × 500 for the most disaggregated tables. These tables usually show the flows between industrial sectors at basic prices: neither trade margins nor taxes and subsidies are taken into account to quantify trade flows.

2.2 Formal framework

The different matrices that have been introduced hereinbefore are strongly connected to each other. Their individual properties and the relationships between them will be laid out here.

2.2.1 Basics

Technically speaking, the core of input-output analysis is the A-matrix, which contains all the information about the industrial profile of any region. A is called "inter-industry", or "technology" matrix, because it reflects the technology profile of an economy. This matrix has as many inputs as outputs, in a product-by-product matrix each element a_{ij} in this matrix gives the amount of monetary input from sector i which is necessary to produce one monetary unit of product j; hence A is square by definition. Similarly, in an industry-by-industry matrix, each term represents how much money from industry i is needed to meet the requirements for the output of one monetary unit from industry j. For example, $a_{electricity \rightarrow metallurgy}$ denotes how many M€ (or \$, NOK. . .) are necessary to generate 1 M€ worth of products from the metallurgical industry. When a final demand y is imposed to the system, we are able to know what the total amount of industry or product output x is necessary to meet this demand. The total production equals the internal (inter-industry) production plus the exogenous demand itself:

$$x = Ax + y \tag{2.1}$$

We can derive x:

$$x = (I - A)^{-1} y \tag{2.2}$$

Furthermore, it is possible to introduce two other matrices, S and C, stressor and characterisation matrices respectively. In an industry-by-industry framework,

$$\text{size}(S) = \text{stressors} \times \text{industries}$$

$$\text{size}(C) = \text{impacts} \times \text{stressors}$$

The amount of stressors that is generated by the system can then be denoted:

$$e = S(I - A)^{-1}y \tag{2.3}$$

and the impact:

$$d = CS(I - A)^{-1}y \tag{2.4}$$

The S-matrix associates stressors with industries, analogously to an A matrix where emissions would be (negative) inputs. It is then equivalent to a listing of emissions, per unit of output in each process. C associates impacts with stressors, thanks to weighting factors. For instance, 1 kg of sulphur hexafluoride has the same global warming potential (GDP) as 22,200 kg of carbon dioxide, while 1 kg of methane is equivalent to 23 kg of CO_2. Another important matrix can be derived: Z, the inter-industry flow matrix, which shows the total flows between any couple of sectors cumulated over one year (generally). It is calculated as follows:

$$Z = A\hat{x} = A\widehat{Ly} = A\widehat{(I - A)^{-1}y} \tag{2.5}$$

where I is an identity matrix with the same dimensions as A (and Z, consequently). This relation is crucial, as the data are often retrieved as Z matrices. If one wants to derive A, the opposite operation is valid:

$$A = Z\hat{x}^{-1} \tag{2.6}$$

2.2.2 Building symmetric A matrices

A challenge arises when it comes to construct a symmetric input-output table (SIOT), which is the core of IO analysis, as stated before. The point is that one process is often associated with one product, but it is not the case in reality: several products can generally be generated from a same process whereas different processes can produce the same commodity. Consequently, in a SIOT the total product output is distinct from industry output, q (product output) and g (industries output). Two different matrices must also be built, which are the two pillars to any SIOT: the make (M, which shows what products are generated by industries) and use (U, presenting which products industries use) matrices. Three additional matrices can be immediately derived from this basic set (^{t} denotes a transposing operation):

- The use coefficient matrix

  $$B = U\hat{g}^{-1} \tag{2.7}$$

  which represents the proportion of each commodity used by each industry,

- The market share matrix
$$D = M^t \hat{q}^{-1} \tag{2.8}$$
which describes which industries produce which products,

- The product mix matrix
$$C = M\hat{g}^{-1} \tag{2.9}$$
which indicates the share of each product in the total output of each industry.

Those three building bricks will now help to construct several SIOTs. Indeed, two main assumptions can be alternatively considered, and two classifications can be taken into account (product-by-product or industry-by-industry) leading to four possibilities to model a final symmetric table.

This short part illustrates the main ways to make symmetric input-output tables. It can be noticed that these technicalities have not been extensively used in the present study. However, they have been utilised to fix data discrepancies, e.g. regarding the Czech input-output table which had to be reconstructed from supply and use tables. the United Nations (1999) have created a very comprehensive manual to compile input-output tables, more details can be found in their *Handbook of IO tables compilation and analysis.* The equations presented hereafter are valid for a system with m products and n industries.

Industry-by-industry matrix using the industry technology assumption

Here we assume that the same technology will be employed for all the products, in each industry. This assumption is then called “Industry Technology assumption”. Basically, industry A will fabricate all the products that it is supposed to supply *exactly in the same way*, same hypothesis for industry B, even though it can produce the same commodities as A: two strictly identical products may then be generated in a very different way. Under this assumption, we must use the following equation:

$$A_{IT,nn} = DB \tag{2.10}$$

Where D is the market share matrix, and B is the use coefficient matrix.

Product-by-product matrix using the industry technology assumption

We take into account the same assumption as before. However, here we try to determine the intermediate product requirements per unit of each product. The expression used here is the following:

$$A_{IT,mm} = BD \tag{2.11}$$

Where B and D are exactly the same matrices as above.

Industry-by-industry matrix using the product technology assumption

The hypothesis will now be that each type of commodity produced is produced with exactly the same technology, regardless of the industry which fabricates it. The so-called "Commodity Technology assumption" will then be used. The expression hereafter will be used:

$$A_{CT,nn} = C^{-1}B \tag{2.12}$$

Where B is still the same and C stands for the product mix matrix.

Product-by-product matrix using the product technology assumption

Now, the last combination can give us an idea of the requirements of each product per product necessary to satisfy the intermediate production under the commodity technology assumption. Our last equation will then be:

$$A_{CT,mm} = BC^{-1} \tag{2.13}$$

Note that under this assumption matrix C is supposedly invertible, implying that it has to be square: the number of industries must be the same as the number of commodities.

2.3 Multi-regional input-output

Production and consumption are naturally interlinked units in the economic system. Due to globalisation and international trade, a commodity is not necessarily produced in the same geographical region as it is consumed or used. In a one-region model, the link between domestic production and imported commodities are often assumed to be dealt with assuming domestic technology. This however, leads to great errors if trade regions have diverging technology (Peters & Hertwich, 2006). Another issue which is not resolved by one-region models is the fact that imports and exports in a region or country are satisfying either intermediate or final demand in the recipient region (Peters, 2007). The fundamentals of input-output analysis (IOA) are adapted from the work of Wassily Leontief (Leontief, 1970) and further developed by Miller & Blair (1985). The total economic output (x) in a region is calculated from the sum of intermediate (Ax) and net final demand (y):

$$x = Ax + y \tag{2.14}$$

The net final demand consists of the sum of domestic final demand of domestic produced products (y^d) and final demand for products which are exported (y^{ex}), minus imported products used in final demand (M):

$$y = y^d + y^{ex} - m \tag{2.15}$$

The industry requirements also include imports, which are denoted A^{im}. The remaining part of A is the domestic share A^d. To balance this, the final demand has a new component, y^{im}, which is the final demand of imports (the United Nations, 1999). Equation 2.14 then becomes,

$$x = (A^d + A^{im})x + y^d + y^{ex} + y^{im} - M \tag{2.16}$$

and the import balance must be obtained,

$$M = A^{im}x + y^{im} \tag{2.17}$$

giving:

$$y = A^d y + y^d + y^{ex} \tag{2.18}$$

which is the domestic activity of a given region. In order to include other activity than domestic, not assuming domestic technology, a multi-region framework can be useful. The multi-region input-output (MRIO) model helps to determine which regions a certain activity is located and how much of this is pulled by a demand in other regions (Peters & Hertwich, 2006). The demand of one product from another country could induce a demand of another product within the same region required in order for the other country to produce the initially demanded product. E.g. a Norwegian lumber company's demand of Swedish furniture could induce a demand of Norwegian wood to Sweden. The MRIO framework extends the IOA model, giving a new system consisting of multiple regions. An n-region system with focus on domestic region $i = 1$ will then be (Peters & Hertwich, 2006):

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & A_{n3} & \dots & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{n1} \end{pmatrix} \tag{2.19}$$

The model will change accordingly for other values of i. The domestic industry demand is on the diagonals in the A-matrix and imports and exports on the non-diagonals. This framework is applicable with traditional IOA theory, one of them being calculation of emissions, which is treated in the next section. In theory, the MRIO framework could be undertaken with IO data for all the countries in the world. This is however utopia/nightmare for IO researchers, and in reality the data availability is more sparse. Currently, there are good data on most OECD countries. Non-OECD however are hard come by. There are two major ongoing projects on developing MRIO datasets. The first one is the Global Trade Analysis project (GTAP) which is out now with version 7 of their MRIO model (Badri & Terrie, 2008). This includes 113 regions with 57 sectors. Another MRIO project is EXIOPOL which will be a global multi-regional environmentally extended input-output database. The work is supported by the EU 6th framework, leading naturally to that the framework is having higher detail on EU-27. EXIOPOL aims to cover around 130 sectors and products (Tukker *et al.*, 2008).

2.4 Environmental extensions

As the input-output matrices describe economical trade between producers and users, this information may also be used to see the environmental repercussions initiated by these flows. This could be done either by adding environmental coefficients to the economical framework or replace the economic flows completely by physical flows. As the former is the most widely used (Joshi, 2000), and will as well be the one used in this report, this method only will be discussed.

The input-output technique may be extended for environmental analysis, by adding a matrix of environmental burdens coefficients. Suppose S is such a $k \times j$ matrix, were s_{kj} is the environmental burden k (e.g. carbon dioxide emissions) per monetary output of sector j. The vector e, representing the total environmental burden due to total monetary output, can then be written:

$$E = Sx = S(I - A)^{-1}y \tag{2.20}$$

The environmental burden matrix S may include coefficients for all environmental impacts of interest, such as carbon dioxide emissions or energy use, as well as use of non-renewable resources.

Finally, a "characterisation" matrix C is commonly used to transform the stressor amounts listed in E to some more accessible impact, e.g. global warming potential (GWP). The characterization matrix lists each stressor's contribution to each environmental impact, relative to some reference compound, so that the E vector is converted into total impacts in terms of emission equivalents of the reference compound. The vector of total impacts d, then, is calculated as follows:

$$d = Ce = CSx = CS(I - A)^{-1}y \tag{2.21}$$

Variations of this general equation can be used to provide useful information on a more detailed level. The most straightforward is perhaps the equation

$$E = \hat{S}x \tag{2.22}$$

which breaks the emissions down sector-wise, such that E_{ij} represents total direct emissions of stressor i from sector j. An even more detailed representation of emission flows can be obtained from the equation

$$E^{f.d.} = \hat{s}L\hat{y} \tag{2.23}$$

where an element $E^{f.d.}_{ij}$ represents total emissions from sector i due to the final demand of sector j's output. By excluding the final demand y from the latter equation, we obtain a similar matrix which instead gives corresponding emissions per unit final demand on each sector.

It is also possible to measure the emissions associated with each round of production, using what is known as *tier expansion analysis*. To meet the demand y, additional production on top of producing the final demand itself will be necessary. The first round ("tier 1") will be $x_1 = Ay$. These requirements will be fulfilled by the second production round, $x_2 = Ax_1 = A^2y$. Consequently, the impact associated with tier n can be written:

$$d_n = CSA^n y \tag{2.24}$$

and the cumulative impact after n tiers:

$$d_{n,acc} = CS\sum_{i=0}^{n} A^i y \tag{2.25}$$

Note that as n approaches infinity, we get $\lim\limits_{n\to\infty} d_{n,acc} = CS(I-A)^{-1}y = d$. For more details about Taylor series tier expansion, see appendix A.

When applying the above equations to study emissions in an MRIO, it is of interest to make certain distinctions. Commonly, we wish to study the total emissions of a certain country or region, and determine how much of these are due to production of exported goods. This is referred to as "emissions embodied in trade" (EET). Using equation 2.20 above, we can extract parts of A and y to determine the EET from region r to region s:

$$EET_{rs} = S_r(I - A_{rr})^{-1}e_{rs} \tag{2.26}$$

where e_{rs} is the vector of total exports from region r to region s.

From the "polluter pays" principle, it is useful to distribute total emissions according to the final consumption they serve. To this end, we introduce the concept of "emissions embodied in consumption" (EEC). To calculate this, we need to separate exports from region r to region s into exports to industries and exports to final demand: $e_{rs} = e^{ii} + y$. EEC differs from EET in that it gives total emissions initiated by a final demand. Hence, the equation giving EEC becomes:

$$EEC_r = S(I - A)y_r^{EEC} \tag{2.27}$$

where y_r^{EEC} is region r's domestic plus imported final demand.

2.5 Environmentally-extended input-output analysis

Even though basic environmentally extended input-output analysis has the advantage of a broad and complete system boundary, there are still some important limitations of the model that will be dealt with in the following section. Most of it is a summary of an article by Joshi (2000) published in the Journal of Industrial Ecology.

The sectors in the input-output model are often largely aggregated, and one sector may include a large number of products. This could result in difficulties when there is a need for comparing products within a commodity sector. A high level of aggregation could also be problematic if the product of interest differs highly from the main output of its commodity sector. Additionally, when studying completely new sectors, a basic EEIO is not sufficient. In order to overcome these limitations, certain extensions of the basic EIO-LCA model need to be made. This could be done in many different ways, and the following sections deal with the three approaches that have been undertaken in this project in order to make the extended EIO-LCA able to analyse the environmental burdens associated with one specific product.

2.5.1 Approach 1: Approximating the product by its sector

In this approach it is assumed that the technical and environmental characteristic of the product of interest is similar to its industry sector. By assuming this the product can be studied by changing the output due to a changing final demand. An implicit assumption for this approach is a proportional relationship between the product price, the environmental burden and the industrial input. This approach is useful when studying broad industry sectors, or outputs that are typical for industry sectors.

2.5.2 Approach 2: Product as a new hypothetical industry sector

When studying a product that is not typical for its industry sector, or when studying a new technology, a new industry sector could be added to the model as a hypothetical industry sector entering the economy. In this approach data on the industrial inputs to - and the direct emissions from the added industry sector need to be available. For an economy with n sectors, one can assume that the new industry is represented as sector $n+1$. $a_{i,n+1}$ is then the monetary value of input required from sector i to produce one unit of the new product. It is here assumed that the inputs to the new product are representative outputs from their respective industry sectors. This gives the reformulated technical coefficient matrix

$$A = \begin{pmatrix} a & a_{i,n+1} \\ 0 & a_{n+1} \end{pmatrix} \tag{2.28}$$

Similarly, the environmental impact vector for the new industry sector, s_{n+1}, is added to the environmental burden matrix, giving the new matrix

$$S = \begin{pmatrix} s_1 & \dots & s_n & s_{n+1} \end{pmatrix} \tag{2.29}$$

The environmental impacts associated with an output of the new sector are then found by the expression

$$E = Sx = S(I-A)^{-1}y = SLy \tag{2.30}$$

Where y is the final demand for an output y_{n+1} of the new sector

$$y = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ y_{n+1} \end{pmatrix} \tag{2.31}$$

2.5.3 Approach 3: Disaggregating an existing industry sector

By adding a new hypothetical industry sector one has to make the assumption that the original coefficient matrix is unaffected by the introduction of a new sector. This will not be the case when the product of interest is already included in an existing industry sector. In this case the industry that includes the sector of interest, say industry n, could be disaggregated into two sectors, one containing only the sector of interest, and the other containing all other products of the original sector. The sector of interest will hence be introduced as a new sector $n+1$, and a new technical coefficient matrix with dimension $(n+1) \times (n+1)$ must be derived. The first $n-1$ sectors of the new coefficient matrix are similar to the ones in the original coefficient matrix, A^{orig}. The purchases of sector j from sector n and $n+1$ is similar to the purchases of sector j from sector n in the old coefficient matrix.

$$A^{orig}_{n,j} = A^{adj}_{n,j} + A^{adj}_{n+1,j} \tag{2.32}$$

If k represents the share that the product of interest makes of the output of the original industry sector, the following equation gives a constraint on the coefficients of A^{adj}:

$$A^{orig}_{n,n} = (1-k)(A^{adj}_{n,n} + A^{adj}_{n+1,n}) + k(A^{adj}_{n,n+1} + A^{adj}_{n+1,n+1}) \tag{2.33}$$

The share of the product of interest can be obtained from external sources. The technical coefficients for the product of interest, $A_{i,n+1}$, can be estimated from detailed cost data of the product. Additionally, data on the sales of the new product sector must be available in order to estimate $A_{n+1,j}$. In order to extend the environmental stressor matrix the direct emissions from the product of interest needs to be known. The stressor from producing the output of the original sector, r_n, is then disaggregated the following way:

$$S^{orig}_{n} = (1-k)S^{adj}_{n} + kS^{adj}_{n+1} \tag{2.34}$$

One of the main differences between LCA and input-output is the origin of the input data: process-based data, from inventories at a local scale, for LCA, whereas Input-Output is based on data collected by statistical agencies. In other terms, even though LCA and IO are quite similar regarding their way of treating data, the former relies on a bottom-up approach, while the latter is more of a top-down method. The complementarity of both techniques can be exploited due to a hybridisation treatment. The approach to hybridisation is illustrated in figure 2.1.

A_{bb}, v_b, s_b, s_{hh} and y_b are usually retrieved from national statistics bureaux, while the other parts of the system come from life cycle inventories. Therefore, hybrid LCA/IO analysis models are usually mixed-units matrices: A_{ff} is in physical units per physical units, A_{bf} in monetary units per physical units (prices), A_{fb} in physical units per monetary units and the background system remains as it is when it has been gathered, in monetary units per monetary units.

It should be mentioned that all the pieces of this jigsaw contain values on a per-unit basis. Consequently, they are representative of the average technology of a country. Nonetheless there is an exception since y is the total final demand, it is usually summed over one year and represents absolute flows. Besides, this expresses the fact that consumption drives the whole economy of a country.

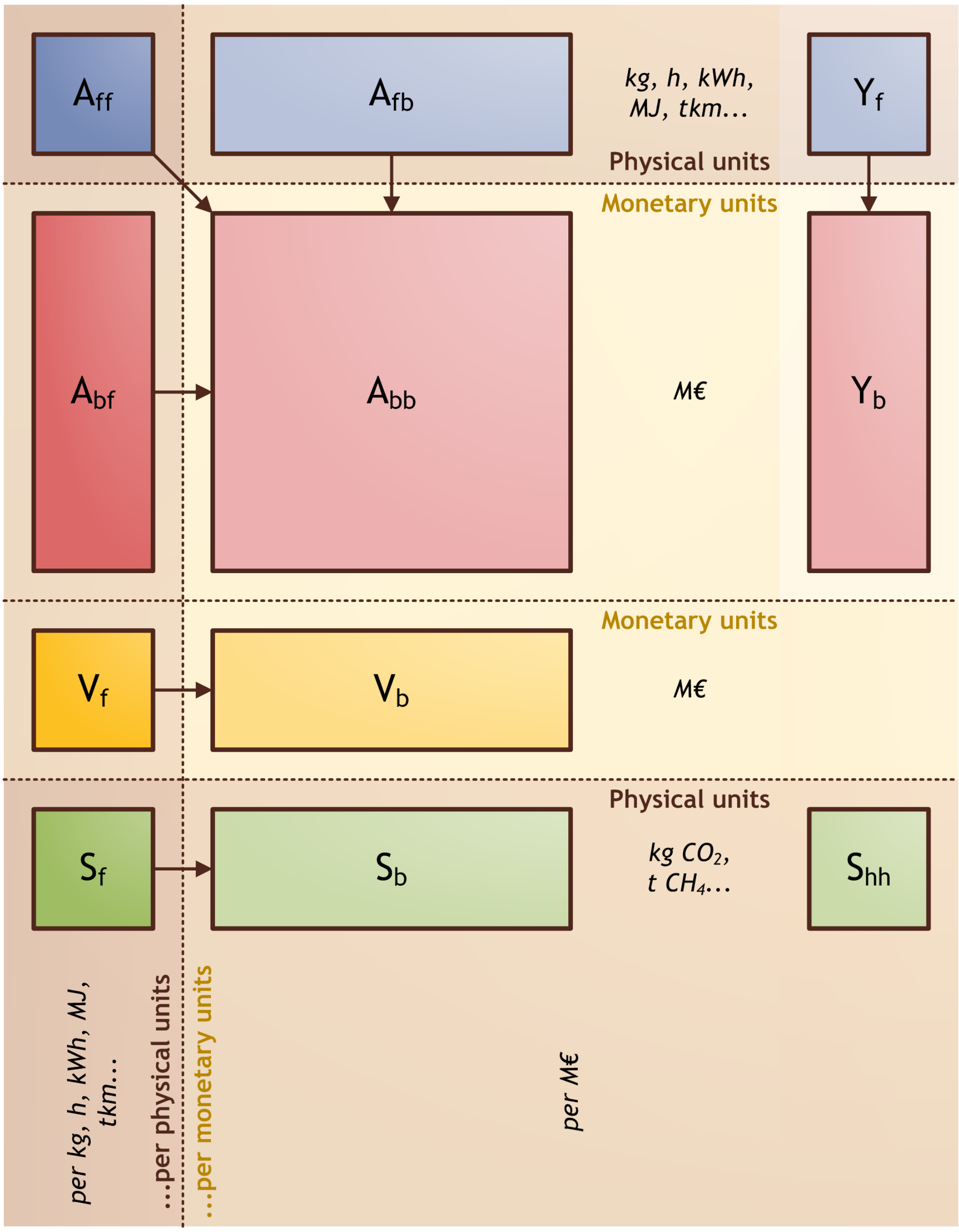


Figure 2.1: Conceptual hybrid LCA/input-output framework. A_{ij} are the technology matrices from i to j, alternatively b (background) or f (foreground). The final demand vector (or matrix) is y, V is the value added vector (or matrix) while S stands for “stressors” and denotes the matrix gathering per-unit emissions. The small part S_{hh} contains emissions from households.

Chapter 3

Building a multi-regional input-output table

This chapter represents a substantial share of the work that has been produced for this master thesis. The same four additional authors (as for the previous chapter) have to be credited for the writing process. The content of this chapter encompasses all the steps that have been needed in order to build a multi-regional input-output (MRIO). This MRIO aims at covering the world trade flows, between 23 European countries and the rest of the world, disaggregated in 8 geographical regions.

3.1 Compiling the inter-industry and final demand matrices Z and y

The very first step is to model the core of the MRIO framework: the inter-industry and final demand monetary flows, gathered in the matrices Z and y respectively. This has been done according to a protocol that is described in the following sections.

3.1.1 Data collection

The challenge in modelling monetary flows within a country as well as between different regions of the world is to deal with the myriad of sources that are available, trying to connect them with relevant adjustments. Among others, sources that have been used for the construction of those matrices are: the European Statistics Agency (hereafter ESA or Eurostat), the Global Trade Analysis Project (GTAP) database, the International Energy Agency (IEA) and the Olsen and Associates Corporation (OANDA). This section presents how and where data were gathered from. A later section will show how the sources can be connected to each other, since discrepancies are unavoidable, in terms of currency, sector disaggregation or year of collection. The main data, i.e. the flows themselves, were obtained from Eurostat. The reference year is 2000. The nature of the data is quite similar for all of the European countries: tables of 59 NACE sectors, either industry per industry or product by product, including use (at basic and purchaser prices) and supply tables, symmetric input-output tables as well as both domestic and import flows. For a handful of countries, data were not available and some assumptions had to be taken into account. This is mentioned in section 3.1.6. For another couple of countries, product-by-product matrices have served as proxies for industry-by-industry matrices. However, single aggregated import tables are not sufficient when it comes to building a Z-matrix with more than 2 regions. A challenge was therefore to figure out what the import shares from industry to industry and from country to country are. The GTAP data were used for this purpose, as it uses an 87 region world trade model. Throughout the compilation of those matrices into a bigger one, currency conversion had to be processed, relying on rate data gathered from `http://www.oanda.com`.

From Eurostat (2009), the data for the following 23 countries have been retrieved (country code in parentheses):

1. Austria (AT),
2. Belgium (BE),
3. Czech Republic (CZ),
4. Denmark (DK),
5. Estonia (EE),
6. Finland (FI),
7. France (FR),
8. Germany (DE),
9. Hungary (HU),
10. Ireland (IE),
11. Italy (IT),
12. Lithuania (LI),
13. Luxembourg (LU),
14. Malta (MT),
15. the Netherlands (NL),
16. Norway (NO),
17. Poland (PL),
18. Portugal (PT),
19. Slovakia (SK),
20. Slovenia (SI),
21. Spain (ES),
22. Sweden (SE),
23. United Kingdom (UK).

At the starting point, 2 sets of tables are available for each country: domestic and import trade flows. Note that the acronym “EU23” refers to the group of countries that are listed above.

3.1.2 Approach

Computing Z^d_{ii}

The first and simpler operation is the construction of the diagonal area of the Z-matrix. There is indeed only one operation that is to be processed, which is currency conversion, since the monetary unit (million euros, M€) is to be homogeneous all over the matrix. All these domestic matrices are then diagonally stacked together to form the spine of the big Z-matrix.

Computing $Z^m_{ij,i\neq j}$

The method used to obtain the $Z^m_{ij,i\neq j}$ (import) matrices was a breakdown of the import flows from Eurostat database's Z^m's. Fairly accurate information can be found in the GTAP data about each country's import shares. Unfortunately the sector disaggregation (57 × 57) used in this database is different from the NACE-based classification that is to be used in the final output matrix (59 × 59). A bridging operation from 57 × 57 to 59 × 59 had to be processed to get the right import shares that can be utilised to split the import matrix. Note that the GTAP framework assumes an import mix which is similar for all the industries within a country. This means that import shares are actually column vectors. A *bridge* ($B^c_{\text{GTAP}\rightarrow\text{ESA}}$, where c can be any of the considered countries) consists of a void matrix (output dimension × input dimension, or *vice versa*) which is filled with ones where two sectors match, it is a correspondence matrix. Furthermore, in the present case row disaggregation must be processed when a GTAP sector has to be distributed into more than one ESA sector. Shares are obtained from the y^e (export demand) in the ESA data. Formally,

$$b^c_{ij} = \frac{b^c_{ij,unit} y^e_i}{\displaystyle\sum_{1\leq i\leq 59} b^c_{ij,unit} y^e_i} \tag{3.1}$$

$$\forall \{i,j\} \in \{[[1,59]],[[1,57]]\}$$

where b^c_{ij} is the element at row i and column j from the bridge matrix for country c. Besides, $b_{ij,unit}$ stands for the element (i,j) of a bridge matrix with only values zero or one, being rather a correspondence matrix.

As far as the shares are concerned,

$$\text{shares}_{\text{GTAP},ij} = \frac{\check{Z}_{\text{GTAP},kl}}{\displaystyle\sum_{1\leq j\leq 87} \check{Z}_{\text{GTAP},kl}} \tag{3.2}$$

$$\forall \{i,j\} \in \{[[1,57]],[[1,87]]\}, k = 57(j-1)+i, l = 57j$$

$\check{Z}$ denotes a regular Z matrix where all the domestic (diagonal) sub-matrices are void. Consequently:

$$\text{shares}_{\text{ESA}} = B^c_{\text{GTAP}\rightarrow\text{ESA}} \text{shares}_{\text{GTAP}} \tag{3.3}$$

A last bridge has to be made in order to match ESA country distribution, from the GTAP 87 country-framework. After that, the shares can finally be applied to every Z^m, all of them completing the Z matrix. Note that currency conversion is also applied at that stage.

3.1.3 World extension

So far, 23 European countries have been taken into account in this model. However, the model aims at being used out of the scope of this study. Then, a "rest of the world" layer has been added *via* the attachment of 8 regions' trade and emissions flows. A total of 31 regions covering the whole global trade is now included in the model. The 8 considered extra-EU23 regions are:

1. Oceania (Oc),
2. China (CN),
3. Asia (As),
4. North America (NA),
5. South America (SA),
6. Rest of Europe (RE),
7. Middle-East (ME),
8. Africa (Af).

The original data for this part of the model are gathered from GTAP (undated). This part of the compilation has been executed by Ph.D. students at the Industrial Ecology Programme at NTNU.

Electricity disaggregation

Electricity production is dealt with as only one sector in the ESA data. However, a disaggregation of this sector is preferable, since different sources are available. Furthermore, the amount of emissions released for the electricity production is likely to vary a lot from source to source. Information about electricity source mixes can be found in the appendix, as retrieved from the International Energy Agency (2009). Regarding this consideration, the concerned sector was broken down into 6 different sectors, each of them being a major electricity producer:

- Hard coal,
- Hydropower,
- Nuclear,

- Wind,
- Natural gas,
- Petroleum and NEC.

To do so, a particular treatment is applied to the preliminary (i.e. not disaggregated yet) Z-matrix, regarding the electricity sector. Since rows and columns should be split in different ways, two disaggregation operations are necessary. The row disaggregation should take into account the various energy mixes, whereas the column disaggregation is somewhat more complex as inputs to each source should be treated one by one. It is indeed important to distribute the inputs in a proper way, coal flows are for instance not to be used by the wind power sector and uranium and thorium are only inputs for the nuclear power production plants.

Row disaggregation This part of the work is rather straightforward; it consists in building bridges for all the countries, from a correspondence matrix (with only value one or value zero) to a bridge taking into account the physical shares of the energy mix. In other terms, ones placed in electricity sectors are substituted by the percentage of the corresponding source. The same kind of disaggregation was applied to the final demand vector, y.

Column disaggregation The bottleneck here is that a simple bridge cannot be directly applied. As explained before, inputs must be treated independently, columnwise. Table 3.1 presents the way inputs were broken down. Each "×" was substituted by the energy mix share of each source, relatively to the other sources which show an "×" on the same row. Basically the sum of each row must always be 1. For instance, the water transportation sector is used by coal- and natural gas-based electricity production sectors. The allocation is then made according to the contribution of each of these sectors to the joint production of coal and natural gas. This table cannot be multiplied with the electricity sector column vector of each Z table, so each column vector here was independently multiplied, term by term, with the electricity vector. As for the sectors that are not mentioned in table 3.1, a distribution over all electricity sources has been made, according to energy shares. At this stage, European countries have 64×64 sectors matrices and rest of the world countries are represented *via* 62×62 matrices. Z_{bb} matrix is ready, and can be represented as in figure 3.1.

3.1.4 Stacking a foreground system

This final step addresses the integration of the foreground system, in order to get

$$\widetilde{Z_{ij}} = \begin{pmatrix} Z_{ff,ij} & Z_{fb,ij} \\ Z_{bf,ij} & Z_{bb,ij} \end{pmatrix} \tag{3.4}$$

Table 3.1: Way the economic flows towards electricity sectors were allocated between 6 different sources. From Hawkins (2009).

	Coal	Natural Gas	Nuclear	Hydro	Wind	Petroleum and NEC
Agriculture, forestry & fishing (01–05)						×
Coal, lignite, peat (10)	×					
Crude petroleum (11.a)						×
Natural gas (11.b)		×				
Other petroleum & gas (11.c)						×
Uranium & thorium ores (12)			×			
Food, apparel, wood, and other (15-22)						×
Coke oven products (23.1)	×					×
Refined petroleum products (23.2)						×
Nuclear fuel (23.3)			×			
Electricity by coal (40.11.a)	×					
Electricity by gas (40.11.b)		×				
Electricity by nuclear (40.11.c)			×			
Electricity by hydro (40.11.d)				×		
Electricity by wind (40.11.e)					×	
Electricity nec, (40.11.f)						×
Railway transport (60.1)	×					
Other land transport (60.2)	×	×	×	×	×	×
Transport via pipelines (60.3)		×				
Sea & coastal transport (61.1)	×	×				
Inland water transport (61.2)	×	×				

$$
\begin{array}{ccccc|ccc}
\multicolumn{5}{c|}{\overbrace{\hspace{22em}}^{\text{EU23, 64 sectors}}} & \multicolumn{3}{c}{\overbrace{\hspace{12em}}^{\text{RoW, 62 sectors}}} \\
Z^d_{AT} & Z^m_{AT\to BE} & Z^m_{AT\to CZ} & \cdots & Z^m_{AT\to UK} & Z_{AT\to Oc} & \cdots & Z_{AT\to Af} \\
Z^m_{BE\to AT} & Z^d_{BE} & Z^m_{BE\to CZ} & \cdots & \vdots & Z_{BE\to Oc} & \cdots & Z_{BE\to Af} \\
Z^m_{CZ\to AT} & Z^m_{CZ\to BE} & \ddots & & \vdots & \vdots & & \vdots \\
\vdots & \vdots & & \ddots & \vdots & \vdots & & \vdots \\
Z^m_{UK\to AT} & \cdots & \cdots & \cdots & Z^d_{UK} & Z^m_{UK\to Oc} & \cdots & Z^m_{UK\to Af} \\
\hline
Z^m_{Oc\to AT} & \cdots & \cdots & \cdots & Z^m_{Oc\to UK} & Z^d_{Oc} & \cdots & Z^m_{Oc\to Af} \\
\vdots & & & & \vdots & \vdots & \ddots & \vdots \\
Z^m_{Af\to AT} & \cdots & \cdots & \cdots & Z^m_{Af\to UK} & Z^m_{Af\to Oc} & \cdots & Z^d_{Af}
\end{array}
$$

Figure 3.1: Disposition of national matrices in the MRIO Z-matrix.

for any $(i, j) \in \{countries \times countries\}$ combination. The whole matrix is denoted $\tilde{Z}$. The same treatment is applied to y, for each couple of country:

$$\widetilde{y_{ij}} = \begin{pmatrix} y_{f,ij} \\ y_{b,ij} \end{pmatrix} \tag{3.5}$$

Since 14 foreground sectors have been added, every domestic matrix now has a new size: 78 × 78. Consequently, any other matrix in the EU23-to-EU23 area has the same size. Rest of the world matrices are not disaggregated to include a foreground-to-foreground system (this is out of the scope), the RoW-to-RoW matrix is still sized as follows 8 × 8 regions with 62 × 62. Obviously, intermediate matrices, EU23-to-RoW and RoW-to-EU23 are resized accordingly. In reality, only 3 foreground systems (i.e. a complete set Z_{ff}, Z_{bf} and Z_{fb}) have been implemented for Finland, Norway and Sweden. Since no other country is assumed to produce DME from black liquor, foreground systems are void matrices for the rest of the European countries.

3.1.5 A matrix

The scenario modelling phase relied on the A matrix, as technology issues were more central than national production schemes and quantities of output. A technical coefficient matrix A can be obtained by dividing each of Z's columns by each corresponding value in g, the product output. Formally, it can be written:

$$A = \tilde{Z} * \hat{g}^{-1} \tag{3.6}$$

3.1.6 Assumptions

Along the compilation, a considerable number of assumptions have been taken into account, depicted below.

Modelling the SIOT

Even before gathering the country import and domestic matrices together, some blanks had to be filled. For instance, the symmetric input-output table (SIOT) for Czech Republic has been calculated from the use table at purchaser prices and the supply table. Using the trade and transport margin column and the taxes less subsidies column from the supply table, a use table at basic prices was estimated, in order to build an industry-by-industry A-matrix, under the industry technology assumption. That way, a Z-matrix has been built for this country. The import column from the supply table was used to split this SIOT into domestic and import tables. More generally, technology assumptions were obviously taken when the other SIOT were compiled.

Import mix

Another point to be noted is that the final Z-matrix inherits the import mix assumption from the GTAP table. In other words, all the industries in Norway import the same distribution of products from Denmark, the same distribution from Sweden, etc.

Electricity disaggregation

Some assumptions have to be unavoidably considered when it comes to disaggregating the electricity sectors. To begin with, the physical flow shares are used to split the row “Electricity production”. This means that the electricity price is constant regardless of what the means of production are. Second, the same energy mix was used when two electricity production sectors (or more) have requirements from the same sector. Finally, some sectors belonging to the same “ESA group” should be accounted differently from source to source, e.g. the sector land transportation gathers railway, road and pipeline transportation. Last but not least, the currency conversion was made according to the average exchange rate to the euro in the year 2000, there is no way to take the rate fluctuations into account as the Z matrices give total flows along the year.

3.2 Compiling the stressor matrix S

A stressor matrix providing industry specific environmental data for all European countries in the multi-regional input-output table were made using the NAMEA framework (National Accounting Matrices with Environmental Accounts). The core of this framework is a set of tables forming a national account matrix (NAM), as it is compiled in national accounts, and environmental accounts in physical units (Eurostat, 2003). Thus, the NAMEA framework provides environmental data in physical units, which is congruent with a national accounting system and nomenclature using monetary accounting (the Organisation for Economic Co-operation and Development, 2009). This makes it a suitable tool for Environmental Input Output analysis. Data from the NAMEA framework were also supplied with country specific environmental data from the Eurostat database where data were lacking. The stressors included in the stressor matrix are CO_2, CO, N_2O, CH_4, NH_3, NO_x, NMVOC, and SO_x. The stressors in the NAMEA framework were consistently compiled with the way economic activities are represented in the national account system used in the input-output table, but a higher order of sector aggregation was occasionally used. This made sector disaggregation essential in order to adapt the emissions data from NAMEA. The input-output table used a 64 sector resolution for the European countries, which the environmental stressors were to be adjusted to. The sector resolution given in the NAMEA framework varied from country to country and provided a different level of detail accurateness. Therefore individual disaggregation of sectors for each country was necessary. Disaggregation was performed based on total output shares derived from the European system of accounts (ESA) from the Eurostat database.

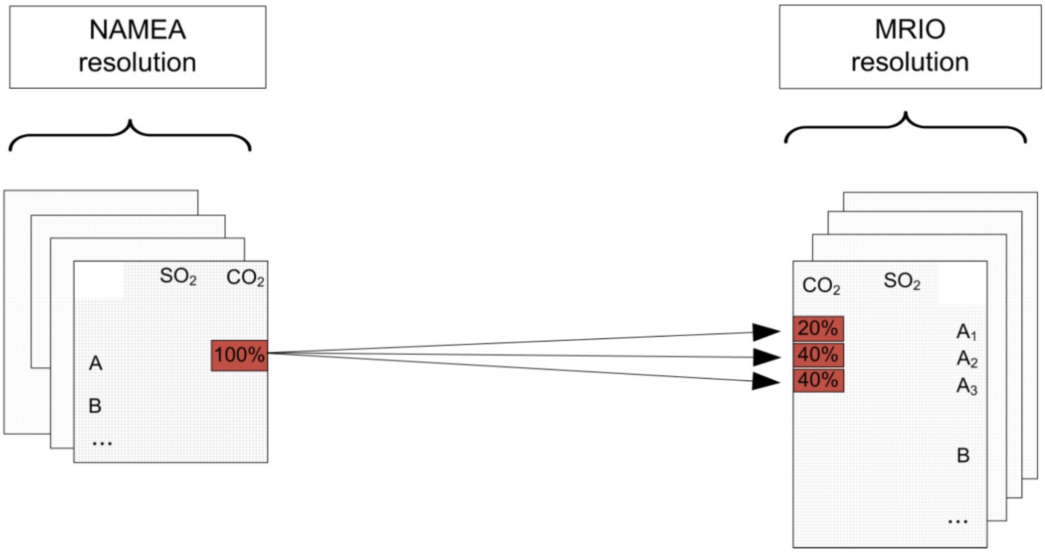


Figure 3.2: Graphical representation of the disaggregation of sectors using the total output shares derived from the European system of national accounts (ESA).

For some countries, the NAMEA stressor data were incomplete, and several assumptions had to be made in order to compile the stressor matrix. Where stressor information was absent for one or more industry sectors, stressor intensities per total output for comparable economies were used. This was later scaled to obtain

Table 3.2: Proxy countries for the *s*-matrix modelling.

Country estimated	Missing data	Proxy country
Austria	All SO_x emissions, various sectors missing	Belgium
Bulgaria	Only total country emissions available	Austria/Belgium
Czech Republic	Only total country emissions available	Belgium
Estonia	Various stressor data missing for CH_4 and CO_2	The Netherlands
Finland	Only total country emissions available	Belgium
France	Data for various sectors lacking	Sweden
Germany	Missing information on CO emissions	Spain
Hungary	Missing CO emissions	Belgium
Ireland	Data for various sectors and stressors lacking	The Netherlands
Lithuania	Only total country emissions available.	Austria/Belgium
Luxembourg	Only total country emissions available.	Austria/Belgium
Malta	Only total country emissions available.	Estonia/The Netherlands
Poland	Various sector data missing	Denmark
Slovakia	Only total country emissions available.	Belgium
Slovenia	Various sector data missing	France

known total emissions for the given country. Stressor intensities were selected from countries with a similar energy profile. The data completeness varied significantly; from a few missing data points to complete lack of data for whole industry sectors or stressor types, cf. table 3.2.

The electricity sector was disaggregated into six electricity sources in order to get more specific data on electricity generation from the stressor matrix. This required specific emission data, which was taken from EcoInvent Centre (2008). The physical data from the database were converted into monetary units using estimated electricity prices for each country. The prices were collected from the International Energy Agency. The electricity sector was disaggregated into coal, nuclear, natural gas, petroleum, hydro and wind power, as seen on figure 3.3.

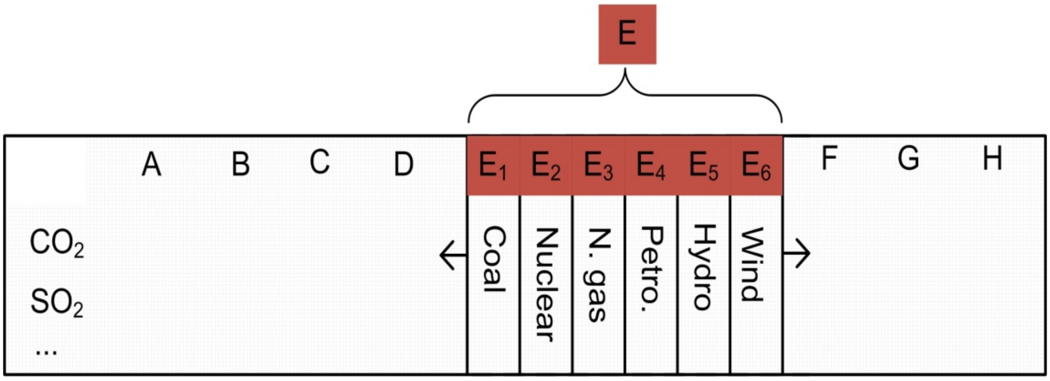


Figure 3.3: Graphical representation of the disaggregation of the electricity sector, in order to obtain more specific environmental data regarding energy use.

3.3 Testing the model

After all the matrix treatment transformations, it is important to check whether the obtained data can be regarded as strong. This can be done quite effortlessly concerning the emissions of carbon dioxide in the year 2000. The following table gathers values from different sources, including the present multi-regional input-output model that has been elaborated in this study. This shows to what extent the results can be considered as reliable.

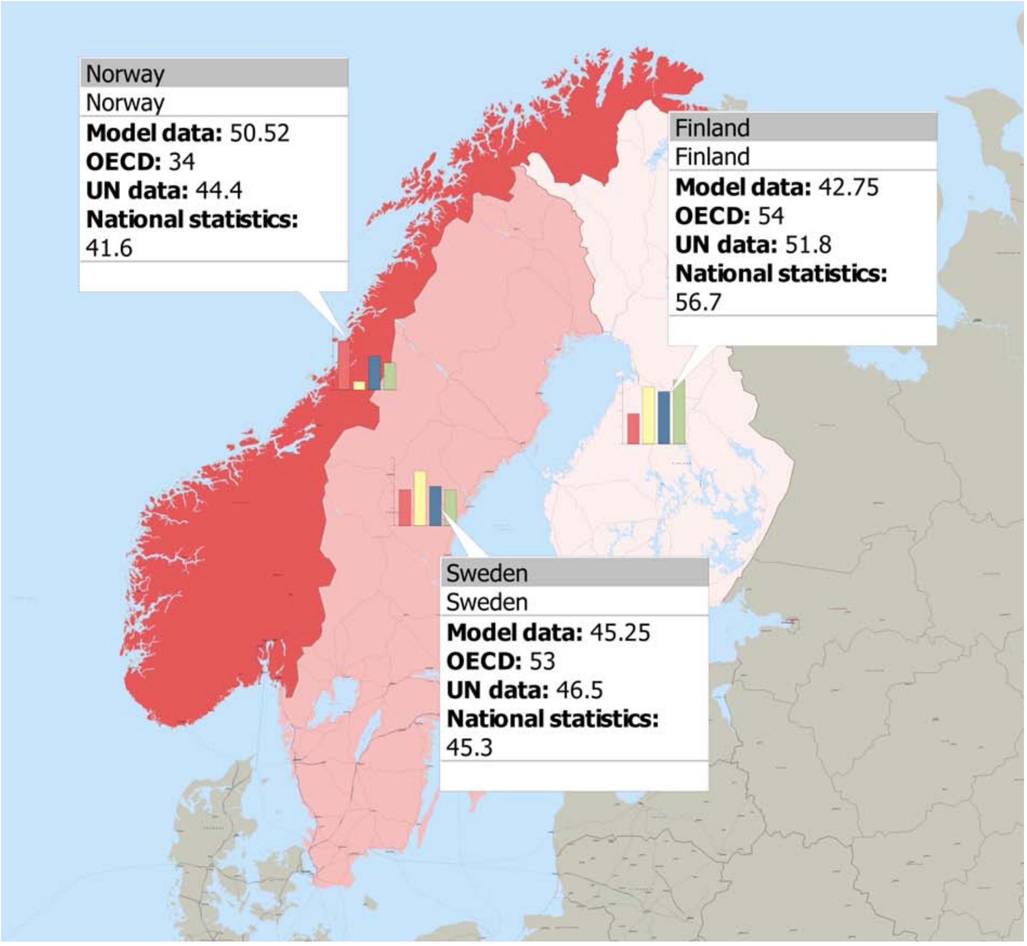


Figure 3.4: Comparison of national emissions figures, in Mt CO_2, in 2000, between the MRIO model results and other sources: the Organisation for Economic Co-operation and Development (2009); Statistics Finland (2009); Statistisk Sentralbyrå (2009); Statistiska Centralbyrån (2009); the United Nations (2009a)

National emissions are shown in figure 3.4. The variation ranges between values from the model and external literature are quite wide but another point has to be raised: even values between official sources diverge quite a lot. This entails two points: (1) the amount of emissions of carbon dioxide released by a national economy is difficult to measure, depending on the approaches that have been used for the emission assessment and (2) some divergences can appear when the bridging from NAMEA categories to ESA's economical sector classification is processed. The stressor matrix used in the MRIO model has indeed been adjusted from the NAMEA made by Eurostat (2009) and proxy countries have been used when needed (when data were not available).

3.4 Data Quality

The quality of the data overall should be fairly good, at least satisfactory for this study. In the Z table, the main assumption made was the import shares (representing interregional trade patterns), which were estimated from corresponding shares from the older GTAP database. This database was also the source of the data for the "rest of the world" region. For the stressor matrix, however, the quality of the data is less certain. The main reason for this is the incompleteness of the NAMEA emission data. Most countries had reported emission data that were more aggregated in terms of economic sectors than the 59 Eurostat sectors, and quite a few countries were missing data for one or more sectors altogether. These holes had to be filled by means of disaggregation and comparison to similar countries. Care should be taken when applying emission data, especially the less "common" emissions, e.g. CO_2 data are generally more comprehensive than SO_x data. Also, larger countries generally report more data than smaller ones.

Chapter 4

Cases, processes and inventories

Swedish and Finnish pulp and paper companies are among the most influential industries of this type in the world. Obviously favoured by vast areas of forests, those countries benefit from a big potential and are able to run an industry sector for which the demand is constantly increasing. In 2000, Finland, Norway and Sweden produced 54.3, 8.16 and 63 million of cubic meters of round wood from their domestic forests (FAOSTAT, 2009). Five firms from the Fenno-Scandinavian area are ranked in the list of the 10 most important European pulp and paper companies. Regarding this potential, the chosen value chain was DME production from black liquor.

4.1 Black Liquor

Black liquor is a by-product of the pulp and paper industry, more specifically of the paper pulp production process. Physically, it is an aqueous solution of lignin residues, hemicelluloses and lignin fragment. See picture 4.1 for a better representation of what black liquor is. It is potentially rich in lignocellulosic compounds, which are the building bricks of second generation biofuels. Black liquor is also a substantial by-product, as the production of one ton of paper pulp can generate 7 tons of black liquor (Biermann, 1993). This substance contains 15–17% solids. By 2000 it is possible to recover up to 99.5% of the black liquor. Most of the challenges concerning pollution issues (black liquor is indeed toxic, particularly to aquatic life) have been tackled now. It is currently incinerated in recovery boilers for steam generation. As explained in the introduction of this report, black liquor recovery is today an integrated process in any pulp and paper mill, making fast implementation plausible. Table 4.1 presents black liquor characteristics. Today's pulp mills often have high-capacity and large recovery boilers. According to Ekbom *et al.* (2003), a large share of European recovery boilers are located in Northern Europe: "about one third of the capacity (and consequently black liquor production) are located in Sweden, one third in Finland and the remainder on the European continent". In other words, as much as *two thirds* of the European potential DME from black liquor production occur in Finland and Sweden, the potential is enormous. Map 4.2 represents the repartition of large capacity boilers across Europe, Finland and Sweden are indisputably leaders in black liquor production. Some high-capacity boilers have been built in Portugal, France and Czech Republic but the fact that Scandinavian countries are taking benefit from the potential of boreal forests is blatant on this map.

Figure 4.1: Black liquor sample, photo by Keith Weller. This picture is in the public domain. Source: `http://www.ars.usda.gov/is/graphics/photos/aug00/k8981-10.htm`.

4.2 Dimethyl Ether

Dimethyl Ether (CH_3OCH_3) is a very promising fuel that can be used either mixed with LPG (up to 30%), with which it shares similar properties, or mixed with regular, conventional diesel (Nexant, 2008). It can be produced through two distinct processes, which share a lot of similarities with production of biomethanol. The first option is to rely on catalytic dehydration of methanol, separating water from pure methanol. The second way is to use syngas (from biomass, typically) as a feedstock, but this technology is still under development. Analogously, the interest of DME use for transportation purposes as a biofuel has raised quite recently, so far it has been used as a substitute propellant for chlorofluorocarbons (Deurwaarder *et al.*, 2007). According to Wang *et al.* (2008), “physical and chemical properties of DME and diesel display mutual solubility at any ratio.” Since 2005, an ambitious state-of-the-art project has been conducted by a Volvo-led consortium in order to build commercial heavy-duty DME vehicles: “BioDME”. The WTT phase is the

Table 4.1: Physico-chemical composition of black liquor (Ekbom *et al.*, 2003).

Chemical composition	
C	35.7%
H	3.7%
S	4.4%
O	35.8%
Na	19.0%
K	1.1%
Cl	0.3%
N	<0.1%
Total	100.0%
Combustible characteristics	
Dry solids	80% mass
HHV	14.50 $\mathrm{MJ/kg_{DM}}$
LHV	12.29 $\mathrm{MJ/kg_{DM}}$

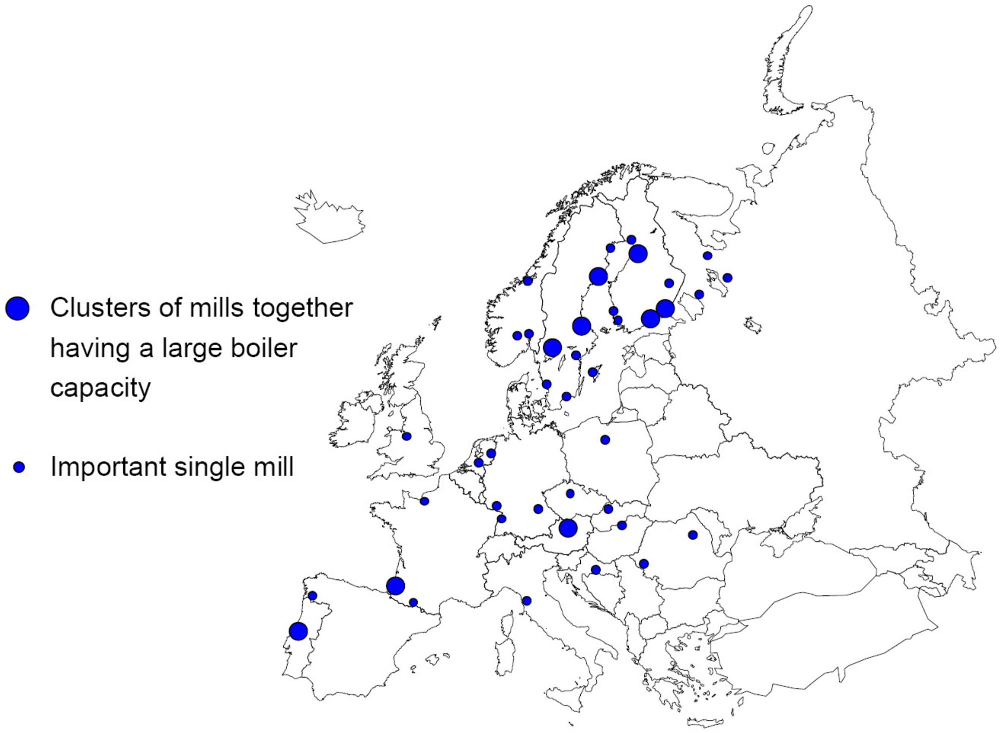


Figure 4.2: Distribution of recovery boilers and their capacities in Europe and consequent production of black liquor, from Ekbom *et al.* (2003).

Table 4.2: Characteristics: diesel and DME fuels.

Property	DME	Diesel	DM10	DM15	DM20
Source	Fleisch *et al.* (1995), Kapus & Ofner (1995), Sorenson & Mikkelsen (1995), Ofner *et al.* (1998)	Wang *et al.* (2006)			
Density (g/cm^3)	0.668	0.840	0.823	0.814	0.803
LHV, MJ/kg	28.43	42.5	41.1	40.4	39.7
Cetane number	55–60	40–55	40–60	40–60	40–60
wt% of carbon	52.2	86.0	82.2	80.9	79.24
wt% of oxygen	34.8	0	3.48	5.22	6.96
wt% of hydrogen	13	14	13.9	13.85	13.8

production of DME from waste liquors from the pulp and paper industry, which plant is located in Piteå, Sweden (Landälv, 2005). As the diesel engine is currently the prime mover for heavy-duty vehicles all around the world, to produce DME could rapidly become a topical issue if its economical and environmental efficiency could be proved at an industrial scale.

In this study, DME will replace fuel that go to the following sectors (in parentheses: NACE name and sector number in the MRIO classification):

- Agriculture ("Agriculture, hunting and related service activities", sector 1),
- Forestry ("Forestry, logging and related service activities", sector 2),
- Construction ("Construction", sector 39),
- Land transportation ("Land transport; transport via pipelines", sector 45),
- Machinery ("Renting of machinery and equipment without operator and of personal and household goods", sector 53).

4.3 Description

This section presents the way A_{ff} and A_{bf} have been filled (cf. figure 2.1). This data collection and modelling phase, which sets the basis for further scenario analysis, is really important. Later on, the A_{fb}-matrix will be modified accordingly to each scenario.

4.3.1 Foreground-to-foreground

According to Renew Project Group (2008), the Chemrec process is divided into several distinct definite steps. However, the earlier biomass production phase could not have been directly from that source, as the kind of feedstock used in the present study is completely different. Subsequently, although the main flows within these inventories were gathered from Renew Project Group (2008), the majority of the figures have been modified in order to fit the cases' geographical and economical context. For instance, a mix of round wood, saw logs, wood chips (i.e. "residues, at forest") and wood waste ("residues, at sawmill") comes as a substitute to the short-rotation wood bundles utilised by the designers of the Chemrec process inventories.

Figure 4.3 shows the different steps, as well as the mass balance value chain of DME. The LCA scope, being more limited than the IOA's one, is indicated on this flowchart.

An extra-block of 14 × 14 sectors was stacked to every original background matrix, in order to introduce these physical flows to the model. Four of those processes are actually representing forestry activities, then nine are processes belonging to the refining chain and the last one is a distribution process. The exhaustive list of processes, with respective units, was then implemented as follows:

- Forestry:
  - Roundwood production (kg),
  - Wood chips (kg),
  - Wood waste (kg),
  - Transportation from forest to plant (tkm).
- Refining:
  - Fuel synthesis plant (1 facility),
  - Dimethyl ether synthesis (h),
  - Gas cleaning (h),
  - Autothermal entrained flow gasification (h),
  - Process specific emissions (kg),
  - Refinery gas (MJ),
  - Heat (MJ),
  - Electricity from plant (kWh),
  - Dimethyl ether, at synthesis plant (kg).
- Final product:
  - Dimethyl ether, at service station (kg).

The number of disaggregated processes may seem to be a bit high, however, the investigated system is added as a new activity to the national economy. This is of most concern to be able to keep track of potential flaws in the way processes

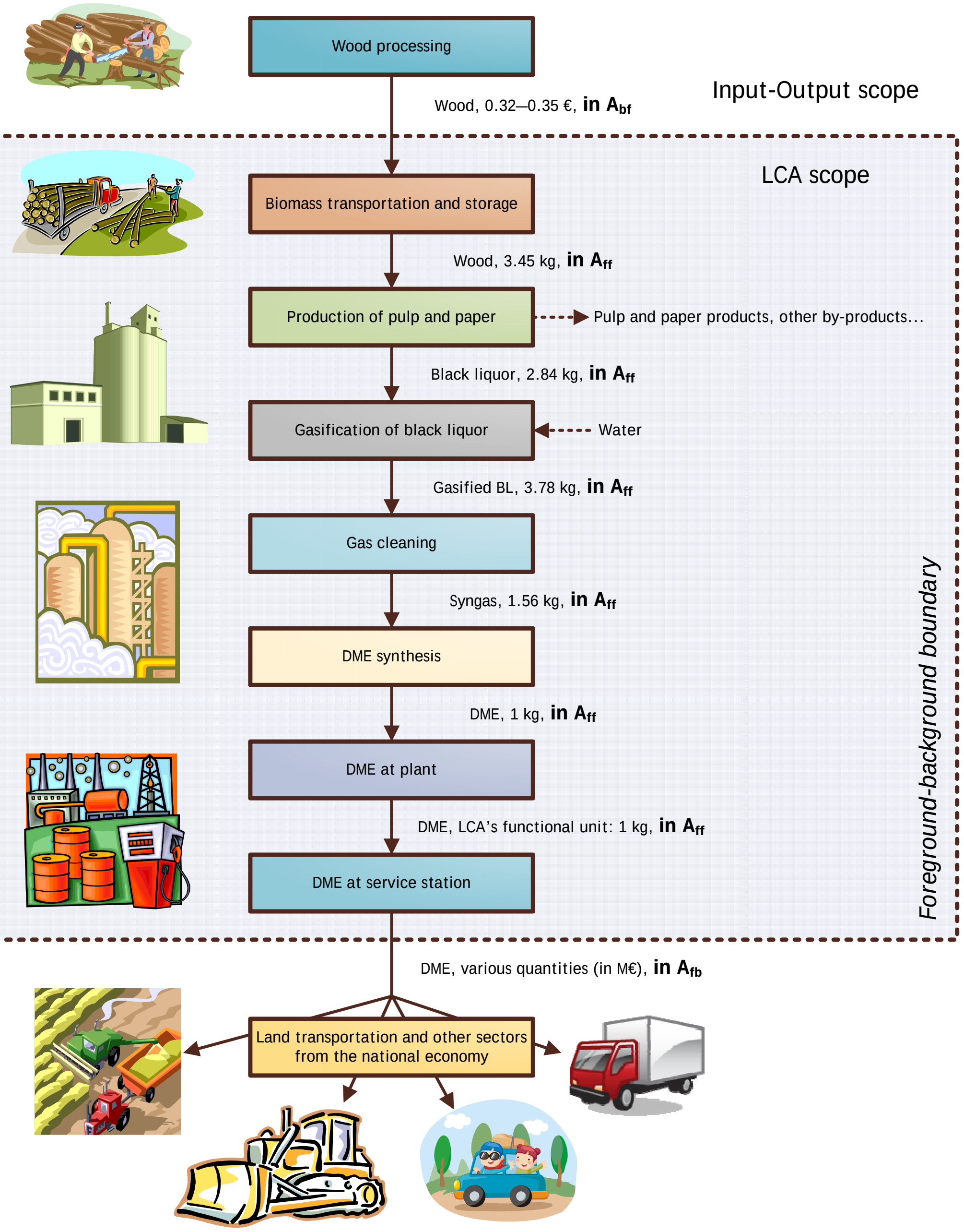


Figure 4.3: Flowchart of DME value chain, with the different scopes and mass or monetary flows.

depend on each other. Basically, using a "black box" inevitably prevents from obtaining transparency in the quantification of the internal flows, within the biofuel production system.

Forestry

The sub-chain called "Forestry" embodies all the physical processes from the cutting operations, at timbered areas, to the transportation of wood chips to the pulp and paper plant. Along this following of processes, various products and by-products are generated: round wood, the raw material itself, wood chips (which are residues from felling) and wood waste (residues from sawing and shredding). The input, waste and emission information about those early processes has been retrieved from EcoInvent Centre (2008), *via* the LCA software SimaPro (Pré Consultants, 2008).

Distances (for these forestry processes) have been adapted from González-García *et al.* (2008), a very thorough environmental impact assessment of wood transportation in south Sweden, central Sweden and Baltic countries. In all these scenarios, the assumed average distance from the forest landing to the pulp mill is 100 km by truck, as well as about 800 km by (electric and diesel) train and 340–461 nautical miles by boat. The transportation scheme in Norway and Sweden then rely on "central Sweden" values, whereas Finnish values are adapted from "south Sweden" and "Baltic countries" scenarios.

It is widely admitted that proper pricing of physical flows is a challenge in input-output. A certain amount of papers can be found about this topic, for instance Weisz & Duchin (2006) who discuss the legitimacy of a physical input-output table, or Suh (2004), who pertinently proposes to replace the price vector by a price matrix. Finding prices for forestry products is challenging, as a lot of sources are available, and a wide panel of products are outputs to the forestry sector. However, the two most comprehensive sources were selected to set the prices that have been used in the foreground system. A comparative table is presented, cf. table 4.3, showing prices calculated from FAOSTAT (2009), where the total physical output of forestry products was available and from Eurostat (2009) and where the total monetary output was simply taken from the SIOT tables. For the conversion from mass to volume, an average value of 500 kg/m^3 was assumed (Simetric, 2009). Prices from the second source were selected, being more homogeneous and coming from a single source, they are supposedly more reliable. In terms of physical quantities, the domestic production figures for round wood are: 54.3 million m^3 for Finland, 8.16 million m^3 for Norway and 63.3 million m^3 for Sweden (FAOSTAT, 2009). As for pulp wood, the same source gives 24.1, 3.37 and 23.8 million m^3 in the same order.

Refining

As mentioned hereinbefore, the original "DME production from black liquor" process chain originally developed by the Chemrec team (*cf. inter alia* Lindblom & Landälv (2007)) utilises short-rotation coppice as a biomass feedstock. The present study aims at assessing the benefits of using the well-timbered areas of Northern Europe. Therefore, one must notice the assumption according to which input of forest wood chips has the same physical and chemical characteristics as willow or poplar woods. The following description of the process is fully adapted from the

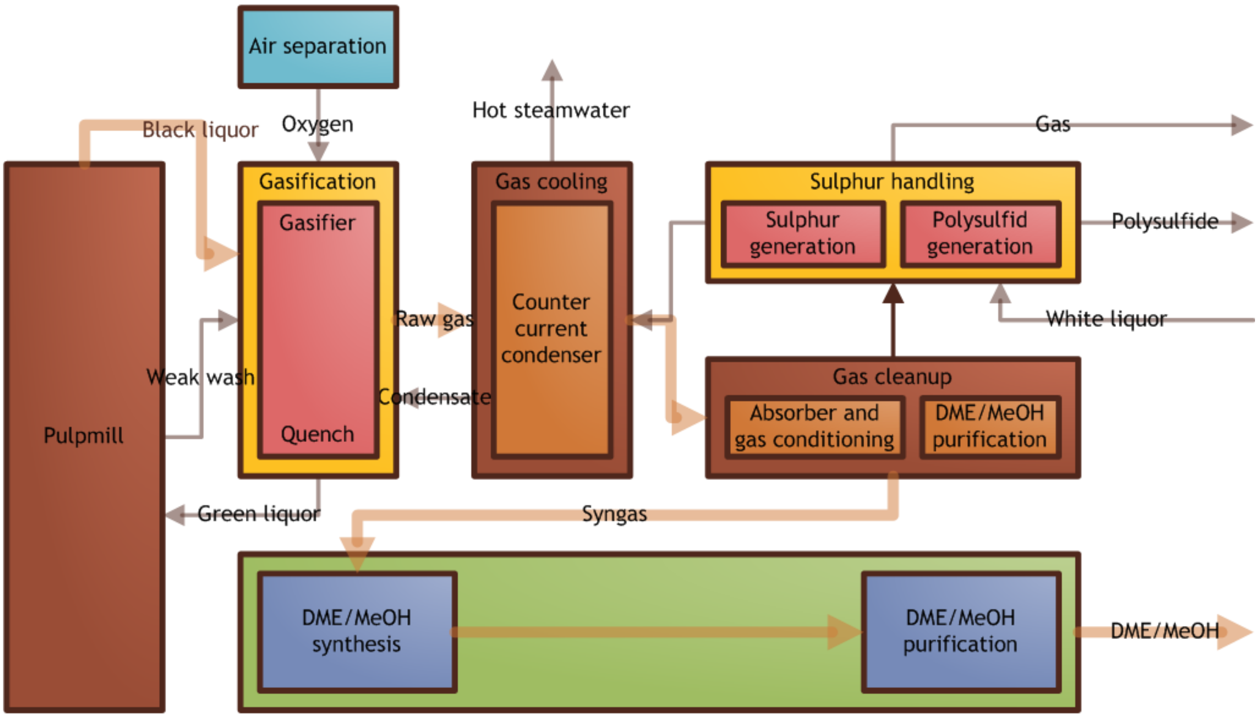


Figure 4.4: Flowchart of pressurised gasification of black liquor, adapted from Jungbluth *et al.* (2008).

Table 4.3: Comparison of the two best available sources for roundwood prices.

Country	Finland	Norway	Sweden
Roundwood prices, calculated from Eurostat (2009); FAOSTAT (2009), €/m^3	57.37	97.63	52.94
€/kg	0.1147	0.1953	0.1059
Roundwood prices, from METLA (2009), €/m^3	46.57	50.44	47.34
€/kg	0.0931	0.1009	0.0947

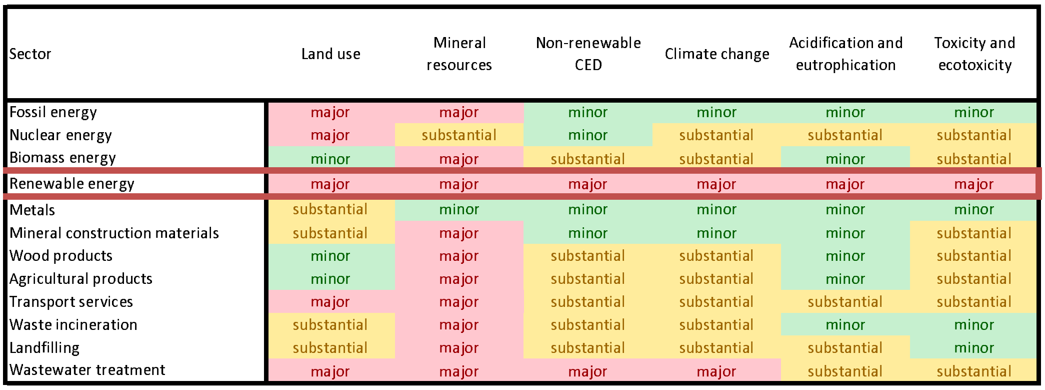
Chemrec process description retrieved from Renew Project Group (2008). One has to note that two integrated processes have actually been developed to recover black liquor with a high-efficiency: the *black liquor gasification combined cycle* (BLGCC) process aims at using the syngas to fire a gas turbine which generates power while the *black liquor gasification with motor fuels production* (BLGMF) process aims at producing biofuel for transportation or similar purposes which use motors. Obviously, the latter process is the one that is investigated in the present study.

The first step of this chain of processes is *gasification*. The integration of this process is fairly simple: in a BLG system, the recovery boiler is replaced by a gasification plant (Ekbom *et al.*, 2006). Therefore, instead of being directly boiled, black liquor goes through a preheating treatment. After being preheated, black liquor enters the pressurised entrained flow gasifiers. It is then gasified with oxygen at high temperatures ($950 - 1000$°C). During this heating, there is a limitation of tar and methane formation. After that, the raw gas is cooled by the spraying of condensate in a quench vessel. A better dissolution rate is achievable by recirculating the quench liquor content via a circulation pump. After a cleaning process ("Gas cleanup" in figure 4.4) the purified gas (syngas) is led towards a DME synthesis part, which is the final step of the whole DME production chain. Note that once again DME is purified before it ends up as fuel-grade dimethyl ether.

Throughout the refining processes, a substantial share of carbon dioxide that is released is actually biogenic. This means that the total global warming impact will be closely related to the few emissions of fossil carbon dioxide that are inherent to the foreground processes or background sectors. This sensitivity implies an accurate bookkeeping of emissions, and physical and monetary flows. The best example of this challenge is the capital goods issue.

Capital goods have to be taken into account to perform a reliable analysis in every life cycle assessment study. Capital goods, mainly consisting of infrastructure processes are indeed explicitly mentioned as part of the product system in ISO standards (14040 series). Furthermore, according to Frischknecht *et al.* (2007), when the main product is associated to a renewable good, the bookkeeping of such processes (plants, storage buildings, machinery...) is necessary. For a better comprehension of this factor, see table 4.4, which shows the relevance of accounting those goods in the inventories. As Frischknecht *et al.* (2007) state, contribution of capital goods to all the impacts (particularly Global Warming Potential) is of most concern, since the commodity itself, so-called "renewable", is not likely to have a substantial environmental footprint. The data were retrieved from Jungbluth *et al.* (2008) and is specifically corresponding to a conversion plant producing dimethyl ether from black liquor. As pulp and paper mills have to be modified and extended to integrate a DME production plant, this is of most concern.

Capital-related issues are also widely discussed in papers by Crawford (2007); Gorree *et al.* (2000); Lenzen (2001), in which capital goods are identified to be considerable contributors to embodied emissions; for some products they found that a 22% share of total emissions can be allocated to capital inputs. The construction of the plant is then represented in the inventory, table 4.5.



Sector	Land use	Mineral resources	Non-renewable CED	Climate change	Acidification and eutrophication	Toxicity and ecotoxicity
Fossil energy	major	major	minor	minor	minor	minor
Nuclear energy	major	substantial	minor	substantial	substantial	substantial
Biomass energy	minor	major	substantial	substantial	minor	substantial
Renewable energy	major	major	major	major	major	major
Metals	substantial	minor	minor	minor	minor	minor
Mineral construction materials	substantial	major	minor	minor	minor	substantial
Wood products	minor	major	substantial	substantial	minor	substantial
Agricultural products	minor	major	substantial	substantial	minor	substantial
Transport services	major	major	substantial	substantial	substantial	substantial
Waste incineration	substantial	major	substantial	substantial	minor	minor
Landfilling	substantial	major	substantial	substantial	substantial	minor
Wastewater treatment	major	major	major	major	substantial	substantial

Table 4.4: Share of impacts caused by capital goods manufacture on cumulative totals and recommendation regarding their inclusion in LCA case studies, from Frischknecht *et al.* (2007).

Distribution

Wang *et al.* (2008) has explored the possibilities of DME/diesel blending, with encouraging conclusions: "All [the study's results] indicate the potential of diesel/DME blend for clean combustion in diesel engines". It literally means that a conceivable 5–20% DME/diesel blend could be used by diesel-fuelled cars without major transformation. Higher rates would imply deeper technological changes. Albeit every engine can theoretically be run with this type of fuel, best expectations will not be met: for improved performances, one must heed about slightly modifying engine characteristics (supply advance angle,...). Since such corrections do not require any special part, but only a few settings, the present study assumes that such an adaptation has a negligible effect on the overall results. As found in Deurwaarder *et al.* (2007), "for DME a similar system as LPG is assumed". This study encompass two transportation models: pipeline transport (Walwijk *et al.*, 1998) and truck transport (Petterson, 2006). The list of inputs for this final node is presented in table 4.6.

4.3.2 Background-to-foreground

The main interest of hybrid LCA/IO analysis relies on this phase of the inventory process. The background-to-foreground matrix is the conversion grid from physical to monetary units. As the foreground system is strongly disaggregated (14 sectors), there is a lesser amount of flows between background and foreground than in a more aggregated system, where one column would gather several processes. The inherent challenge here is to quantify the product flows. It is actually the same issue that we encounter when it comes to fill the foreground-to-background part of the national

Table 4.5: Inventory: DME from BLGMF, 1 kg at plant, FI/NO/SE. Adapted from Jungbluth *et al.* (2008).

Products		
DME at plant	1	kg
Materials/fuels		
Heat, biomass, at steam and power boiler	5.8539	MJ
Refinery gas, burned in flare	0.14962	MJ
Process specific emissions, conversion plant	0.000268	kg
Biomass, incl. storage and preparation	2.33×10^{-5}	h
Autothermal entrained flow gasification, black liquor	2.33×10^{-5}	h
Gas cleaning, black liquor	2.33×10^{-5}	h
Dimethyl ether synthesis, black liquor	2.33×10^{-5}	h
Fuel synthesis plant	2.47×10^{-10}	p

Table 4.6: Inventory: DME from BLGMF, 1 kg at service station, FI/NO/SE. Adapted from Jungbluth *et al.* (2008).

Products		
DME at service station	1	kg
Materials/fuels		
Dimethyl ether, black liquor, at synthesis plant/kg/Chemrec U	1.0004	kg
Electricity, low voltage, production FI/NO/SE, at grid	0.0067036	kWh
Light fuel oil, burned in boiler 100kW, non modulating	0.00062095	MJ
Tap water, at user	0.00068864	kg
Transport, lorry ¿ 16t	0.1	tkm
Transport, freight, rail	0.8	tkm

matrices. The price of the products from each sector has to be retrieved in order to convert the flows into monetary units. Likewise, to be consistent with the rest of the data contained in the background-to-background matrix, import shares have to be considered for some flows. A distinction between domestic and import flows is to be made, mainly based on assumptions. For instance, transportation and woody biomass flows from the background to the foreground are mainly domestic: every country has enough resources in terms of wood, transportation obviously takes place within the country, etc. Contrarily, products that are originally imported (or domestically produced and imported) have also flows that are broken down along the import vectors, such as the zinc input for the gasification process. In the latter situation, the import mix is the same as the products from the most similar sectors (e.g.: "manufacture of basic metals" for the zinc input). One can also mention the need for a price matrix, that would adapt each sector's needs to what they really require, instead of using average values gathered in a price vector. It is obvious that national railway companies do not pay the same fare for 1 kWh of electricity as households or metallurgic industries. This issued is deeply discussed in Suh (2004).

Remark about source diversity

Filling this part of the matrix is a challenging activity when it comes to converting physical flows into monetary flows. For instance, electricity price discrepancies are really substantial from source to source: the Energy Information Administration (2008) shows that industry sectors in Finland pay 0.039 € per kWh of electricity, while Niininen (2009) states that, in 2000, the value of 1 kWh was 0.015 €. These kinds of gaps between figures found in various sources leads to huge differences in the final results of the analysis. Additionally, the more sources, the weaker the model will unavoidably be. Various prices have been tested in the model: aberrant values have been discarded, while prices that made sense (in the range of prices from available sources) have been kept.

4.4 Scenarios

4.4.1 Background

Several policy papers are published on a regular basis by the European Commission. Biofuel-related policies from other regions of the world are presented in the discussion part, but obviously Fenno-Scandinavia is directly concerned by directives voted by the European Parliament. The following is an excerpt of the European Commission directive about the 20-20-20 agreement (Europa, 2007a):

> *What is Europe doing to address* [climate change] *issues?*
> The EU's climate and energy policy sets the following ambitious targets for 2020:
>
> - cutting greenhouse gases by at least 20% of 1990 levels (30% if other developed countries commit to comparable cuts)
> - increasing use of renewables (wind, solar, biomass, etc) to 20% of total energy production (currently 8.5%)
> - cutting energy consumption by 20% of projected 2020 levels – by improving energy efficiency

A business-as-usual scenario will be the baseline for further comparisons. It will model economies where biofuels do not exist and assume that all motor fuels will continue to consume fossil diesel and gasoline. One scenario, known as pulp and paper coupling (or best case scenario, or theoretical maximum scenario) will assess the ideal quantity of DME that can be made of black liquor. Two scenarios can then be added, relying on the two first objectives of this directive, scenario 2 trying to cut as much emissions as possible, and scenario 3 will take into account the infusion of 20% biofuels in the fuel mix in 2020. Actually, the proposed EU energy policy strategy states that alternative fuels in transport should reach 20% by 2020, including 10% of biofuels. Realising the high potential of Fenno-Scandinavian countries, it has been assumed that 20% of biofuels would be an achievable goal. As it seems unrealistic to cut 20% emissions in almost 10 years (the production of DME would be really low in 2010), scenario 2 will model a reasonable but constant increase of demand in DME. The last recommendation of this proposal is to "focus on second generation biofuels", which is totally in accordance with the present study. (Europa, 2007a)

Other policies obviously exist, the one that has been addressed is widely accepted as a reference guideline for most of the European countries. All the scenarios have the same starting point, i.e. pre-DME economies in 2000.

Technicalities

To model the fuel substitution, several steps were implemented into the MATLAB script. There are fairly straightforward and aim at maintaining the same amount of fuel flows and at avoiding double-counting. For each decade (except 2000, where nothing has been changed), the following operations were applied to A, S and y:

1. Decrease the fuel supply in A for sectors "Agriculture, hunting and related service activities", "Forestry, logging and related service activities", "Construction", "Renting of machinery and equipment without operator and of personal and household goods" and in y for all the categories. This can be

done linking the monetary flows from the oil production sector to those industries with the physical flow that can come as a substitute. For example, the fuel supply for agriculture has been modified as such:

$$a^{adj}_{oil \to agr} = (1 - share_{DME}) \times a^{orig}_{oil \to agriculture} \tag{4.1}$$

while the DME flow was set as follows:

$$a_{DME \to agr} = share_{DME} \times a^{orig}_{oil \to agriculture} \times r \tag{4.2}$$

where r denotes the amount of DME that can replace 1M€ of fuel, on an energy equivalence basis. This coefficient was calculated from gas oil prices, densities and LHV of both fuels.

2. The matrix S needs an adaptation as well, as each of the sectors for which fuel supply is shifted towards DME will be less CO_2 intensive. Beforehand, the contribution share of fossil fuels needs to be calculated, in order to know what the amount of each stressor can be mitigated. Then, a similar operation as what has been done in A can be performed. For instance, the CO_2 share is adjusted as follows:

$$s^{adj}_{CO_2} = s^{orig}_{CO_2} \times (1 - share_{DME} * sharefossil) \tag{4.3}$$

There are several ways to substitute the supply of diesel to the sectors in national economy. First of all, (a share of) the domestic diesel production can be substituted by DME. This is for example a strategy adopted by the United States, which owns 16% of the world's oil reserves (the Energy Information Administration, 2009) while being the first importers worldwide, with 13.71 million barrels per day (Central Intelligence Agency, 2005). Second, it could be interesting, from another point of view, to cut the imports, replacing those by domestic biofuel production, in order to become more independent from foreign energy production or policies. Last but not least, a total substitution (regarding domestic fuel production as well as imports) can be imaginable, in the name of environmental consciousness. Strictly speaking, this option would illustrate the predominance of environmental concerns over economic constraints; an approach which is, still nowadays, not very realistic. Nevertheless, the assumption was made for two scenarios that the substitution would either be domestic or total. This is explained figure 4.5.

4.4.2 Final demand

The PRIMES model (Capros *et al.*, 2008) was used to calculate the final demand matrix from 2010 to 2050. PRIMES is a partial equilibrium model for the European Union energy system developed by, and maintained at, the National Technical University of Athens, E3M-Laboratory led by Prof. Capros. The consumption has been assumed to follow the evolution of GDP, the same variation rate has been

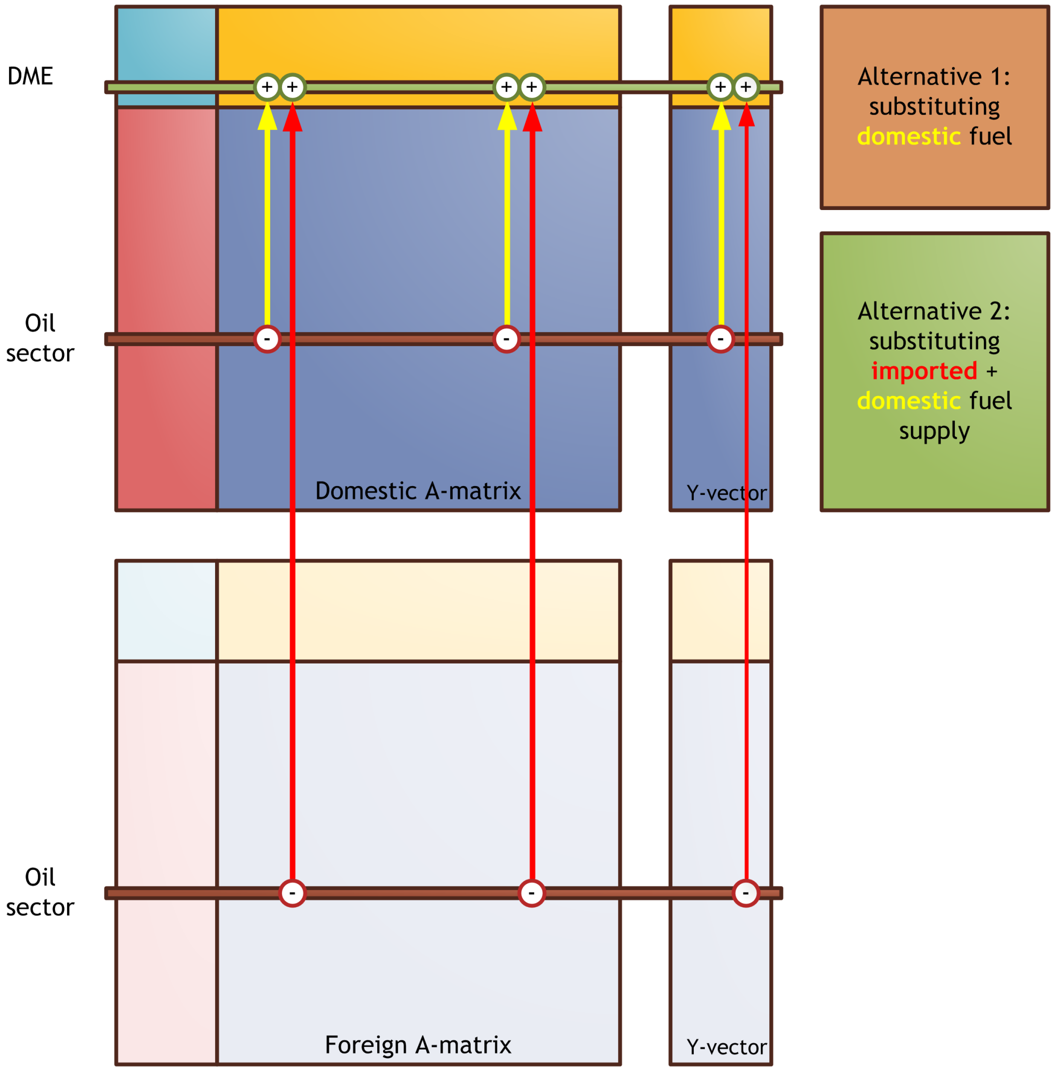


Figure 4.5: Two alternatives are possible for two of the scenarios (2 and 3), either by substituting domestic fuel supply, or by total replacement of both domestic and imported fuel.

applied to all the y-matrix flows that have the same destination country. Table 4.7 presents the figures that have been used for the modelling of final demand, only for Finland, Norway and Sweden. All the values that have been used can be seen in Appendix D. It has to be mentioned that the GDP evolution for Norway does not appear in the last update of the PRIMES report (Capros *et al.*, 2008), the data have been retrieved from a previous version, which is two years older, by Mantzos & Capros (2006). For 2040 and 2050, extrapolations have been used.

Table 4.7: GDP increase for Finland, Norway and Sweden, in %, from Capros *et al.* (2008).

Decade	2000 → 2010	$'10 \rightarrow' 20$	$'20 \rightarrow' 30$	$'30 \rightarrow' 40$	$'40 \rightarrow' 50$
Finland	2.8	1.9	1.4	1.2	1.0
Norway	2.2	2.4	1.9	2.1	1.9
Sweden	2.8	2.3	1.8	1.5	1.3

4.4.3 Scenario 0 – Reference scenario

This is an essential model to address, as a reference is needed in order to compare the potential improvements yielded by the implementation of the technology considered in this present study. In other words, the eventual cut-offs will be calculated from this baseline model, which is obviously a business-as-usual scenario, in which the technology matrix remains the same throughout 30 years. Consequently, no biofuel production scheme is considered here, this assumption likely makes this scenario a worst-case scenario.

The only varying parameter in this scenario is the final demand, coupled with the GDP evolution along the 5 decade-long time span. The emissions are then globally increasing according to the average global GDP increase, weighted according to each country's final consumption flows.

4.4.4 Scenario 1 – Pulp and paper production coupling

This is the most realistic approach, given that the amount of DME produced is supposedly proportional to the quantity of black-liquor produced. Biermann (1993) states that the weight ratio paper/black liquor of an average pulp and paper mill is about 1/7. Furthermore, it is possible to retrieve a range of wood input quantities that are needed to produce different types of paper, from the EcoInvent database. These figures are gathered in table 4.9, an average value will be used to know what the ratio DME/paper is. Ekbom *et al.* (2005) have calculated a biomass-to-fuel efficiency which is equal to 67% in terms of energy, potential production of DME can then be derived, as done in table 4.8.

Table 4.8: Production of black liquor and corresponding amount of DME that can potentially be produced from it, in 2000 (Ekbom *et al.*, 2005; Statistisk Sentralbyrå, 2008).

Country	Black liquor production (PJ)	Potential DME production (Mt)
Finland	143	2.81
Norway	45	0.88
Sweden	139	2.73

The evolution of DME production and pulp and paper total output was modelled as explained hereafter. Obviously, the maximum production levels cannot be met in 2000. Analogously, such production levels are hardly achievable in 2010. Consequently, they have been assumed to be 5% of the maximum levels in 2010, e.g. Finland will produce around 0.2 Mt of DME, instead of 4 Mt, hypothetically. Same thing in 2020, where 50% of the theoretical production is assumed to be reached, 90% in 2030. From 2040, the maximum production pace has been met. Technically, this scenario relies on the results yielded by the baseline scenario, especially pulp and paper industry's total output, from which the amount of DME that can be produced was calculated. In a nutshell, this is nothing but a resource assessment scenario.

4.4.5 Scenario 2

That bottom-up approach is more straightforward regarding the way it could be modeled through a scenario. The infusion rate (i.e. the evolution of DME share in the national fuel mix) would then be constant, making the production of biofuel increase at a regular pace. In some sense, this scenario is more connected to physical counterparts, given that 20% of the fuel will probably not be substituted by biofuels by 2020. The adjustments are indeed directly made on the mix DME/conventional fuel. By 2020, 9% of biofuels would be part of the total fuel mix supply in Fenno-Scandinavia. This has to be connected with the statement European Commission made in their proposal for an Energy Strategy for 2020 (Europa, 2007a) where it is stated that 10% of the fuel share should be biofuels. Modelling a 9% infusion is a conservative assumption that has been made as, as of 2009, no commercial production of DME has been implemented, while a small share of other biofuels already exist.

Table 4.9: Mass balances for various types of pulp, retrieved from EcoInvent Centre (2008).

Pulp mill output type	Wood input per unit output (m^3/kg)	mass ratio
Chemi-thermomechanical pulp	3.087×10^{-3}	1.534
Stone groundwood pulp	3.175×10^{-3}	1.588
Sulphate pulp, unbleached	3.630×10^{-3}	1.815
Sulphate pulp, bleached	4.234×10^{-3}	2.117
Average	3.532×10^{-3}	1.766

4.4.6 Scenario 3

This top-down approach would imply to consider a scenario where the integration of DME in the fuel mix cannot really be calculated. It is indeed challenging to find the accurate rate of infusion of this new technology which would cut the emissions down to 80% the amount that was released in 1990. The realistic aspects of the rate of construction of hypothetical DME production plants are not addressed, in other words, the objective of this scenario is to highlight the extent of the efforts that have to be made in order to meet the 20% cut-off threshold.

4.4.7 Challenges

Subsequently to the setting of the parameters mentioned above, some difficulties appear. Actually, in 2000 there is no commercial production of biofuel in Norway, for example. Then the models will not follow a strict curve that is easily describable with a simple function. Furthermore, in general trends never fit a smooth curve along the years. The PRIMES model gives some predictions for a lot of factors in European countries' economies. The main characteristic of biofuel integration and DME production that entails these bottlenecks is its status of "new technology". For the scenario modeling, the first years' A-matrices will not be changed because of the non-existence of industrial biorefining sector; it is actually unrealistic to set a small production for year 2000, for instance.

A summary of all the assumptions taken is presented in table 4.10. Note that those figures do not exceed the shares that have been found by Ekbom *et al.* (2003). None of these scenarios involves a 100% substitution for several reasons: (1) a total fuel displacement would imply technological adaptation of all vehicles and engines, including those using gasoline, and (2) other biofuels might share the fuel mix with DME from black liquor.

Table 4.10: Variations of parameters for all the scenarios. NB: The share of DME in the fuel mix is not an input parameter for scenario 1.

Parameter							Substitution
Share of DME in fuel mix	2000	2010	2020	2030	2040	2050	
Scenario 0	0%	0%	0%	0%	0%	0%	–
Scenario 1	–	–	–	–	–	–	–
Scenario 2a	0%	3%	9%	26%	52%	75%	dom
Scenario 2b	0%	3%	9%	26%	52%	75%	all
Scenario 3a	0%	7%	20%	30%	40%	50%	dom
Scenario 3b	0%	7%	20%	30%	40%	50%	all
Demand increase	coupled with GDP						

Chapter 5

Results and analysis

This chapter aims at presenting the results of this study according to the different scenarios which were investigated. Additionally, a preliminary section shows basic results and how verifications were addressed. This is a necessary step, given the fact that systems are very sensitive to price and per-unit results. It is also relevant to compare early results with a process-based LCA for example. The "pulp and paper coupling" scenario takes into account the assumption that DME production increases at the same rate as pulp and paper production. Scenarios 2 and 3 are two different approaches inspired from the "20-20 by 2020" directive of the European Commission (2008a). The first scenario (in connection with the pulp and paper output) sets a realistic upper limit to biofuel production; as black liquor is a by-product, it's not possible to produce more DME than what it is possible to get out of that by-product. Those results are either presented in terms of mass of CO_2 or CO_2 equivalents released in the atmosphere. This means one has to care about the units specified on the graphs. There can be significant differences between both values, due to the contribution of dinitrogen monoxide (N_2O) and methane (CH_4). Either unit ([mass] CO_2 or [mass] CO_2 equivalents) can be used according to what the results are going to be compared to. Note that the 5 other stressors inventoried in the S-matrix have not been used for the analysis, as the emphasis has been put on global warming potential, which is internationally recognised as the most important impact in terms of direct effects on the environment. The expression "greenhouse gases" refers to the top trio carbon dioxide, methane and dinitrogen monoxide. As for the countries, Finland is always represented in blue with the abbreviation "FI", while "NO" stands for Norway which is always in red in the graphs, Sweden is yellow and denoted by the abbreviation "SE". When not specified, the unit-level analysis is valid for the year 2000 (current available technology with present economies).

5.1 Unit-level results

The first results that the multi-regional input-output model has yielded are really crucial, as they illustrate the strength and the robustness of the whole framework. Some operations were performed to point out the weaknesses and potential improvements of the model. It appears that linking foreground and background data is something challenging, as it depends on flows which have to be converted from physical to monetary units, or *vice versa.* Conversion factors (prices) are really sensitive parameters, albeit they come from a reliable source, it is really hard to find accurate results, for instance in a comparison with LCA results. Nonetheless, IO is a powerful modelling approach when prices are well-estimated. In fact, the first comparison that can be made is between the process-based LCA and hybrid LCA/IO results. They are very interesting as they illustrate the main differences between the two frameworks, especially when it comes to system boundaries. Namely, since IO has by definition wider boundaries than LCA, calculated emissions are likely lower, per unit of final demand, for the latter approach. Those differences are shown figure 5.1. Performing the basic process-based LCA analysis in SimaPro (Pré Consultants, 2008), the total emissions that correspond to the production of 1 kg of DME in Sweden (as the data come from Renew Project Group (2008), Chemrec project) are found to be 469 g CO_2 for 1 kg DME from black liquor at service station.One can see, on figure 5.1, that there are slight discrepancies from country to country. While the MRIO gives very satisfying results for Norway and Sweden (-0.3% and +1.7% of variation from the LCA data), this is quite different when it comes to Finland. Results for this countries is equivalent to a +13% from the result of the LCA. This small gap between figures is quite surprising, as the original data are nearly the same, with some slight divergences concerning the prices, especially about electricity and transportation. Here are presented more detailed results from the per-unit analysis. The interest of this section is to highlight the “hot spots” along the value chain of each product. No direct emissions (of CO_2 at least) are released in the foreground system, it is then central to know to which sectors the emissions that are embodied in one kilogram of DME should be associated with. Figure 5.1 presents the distribution of sectors that are responsible for emissions of carbon dioxide along the DME value chain (or “value web”). Not surprisingly, transportation, electricity and forestry are the main contributors to global warming potential. One has to remind that only fossil carbon dioxide is accounted here, and transportation mainly relies on fossil fuels in 2000. An interesting point here, which is going to be developed in the discussion, is that DME is principally dedicated to the transportation sector, consequently, the use of DME in land transportation is likely to have a feedback effect on DME’s environmental profile itself. In other words, using DME would make it more environmentally-friendly, the more you use it, the more you should use it. This effect is presented figure 5.2 where the reduction of per-unit emissions is significant. Many parameters are responsible for these savings: the GDP increase model, all the flows in the A-matrix and most of all, the adjusted S-matrix. One can see that the distribution of processes that emit carbon dioxide is quite similar, but the use of biofuel in the national economies have had a terrible effect on the environmental cost generated by the production of one kilogramme of dimethyl ether: a mere 15% cut-off for Sweden, while Norway saves 28% and Finland avoids 57% of the emissions released by the production of exactly the same commodity in 2000. Of course, the foreground system has not been modified, because the same physical flows are still needed to produce DME as no effiency assumptions have been taken into account. Environmentally speaking, Finland becomes the best country where to produce dimethyl ether from black liquor, with only 227 g CO_2 per kg, then Norway remains competitive with 336 g CO_2/kg DME while Sweden still emits a substantial amount of carbon dioxide: 405 g/kg DME. It is also possible to break down the emissions by geographical regions,

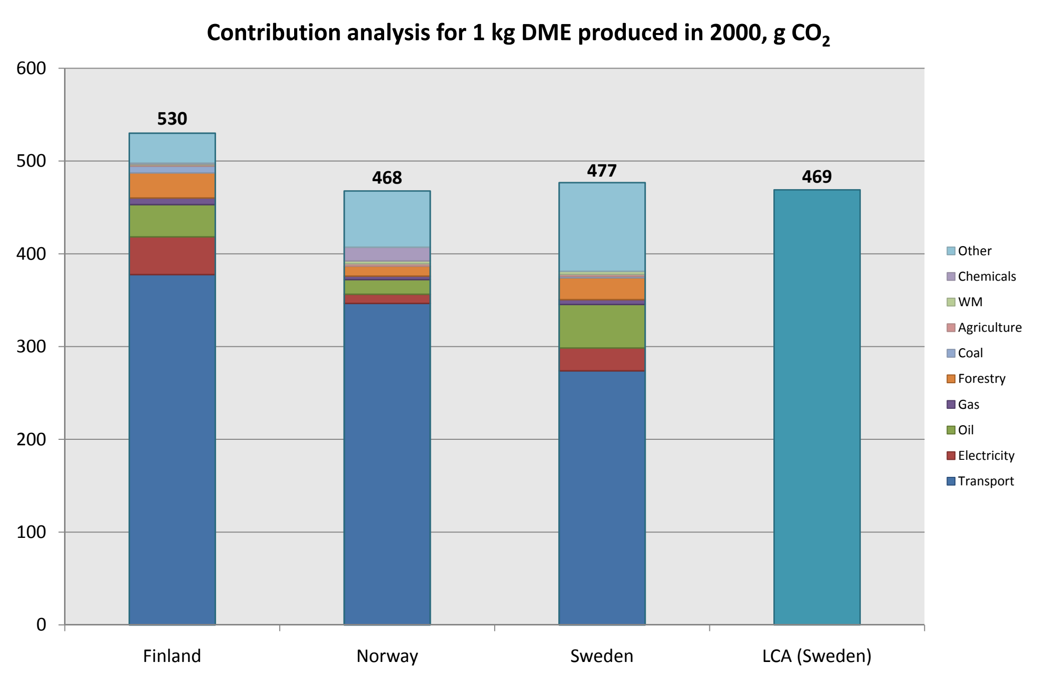


Figure 5.1: Comparison of LCA and IOA approaches, the LCA data have been retrieved from Renew Project Group (2008) and the analysis made with SimaPro 7.1.8 (Pré Consultants, 2008) and contribution analysis. 1 kg of DME from black liquor at service station. “WM” stands for “Waste Management”.

to know where those take place and which share of the final product’s embodied emissions is domestic or foreign. Figure 5.3 shows the emissions embodied in trade, i.e. import- and domestic-related emissions. Peculiarly, the share of emissions associated with domestic industries varies significantly from country to country. While 81% and 78% of the CO_2 released by the production of 1 kg of DME in Finland and Norway, respectively, are associated with domestic activities, a mere 45% (of

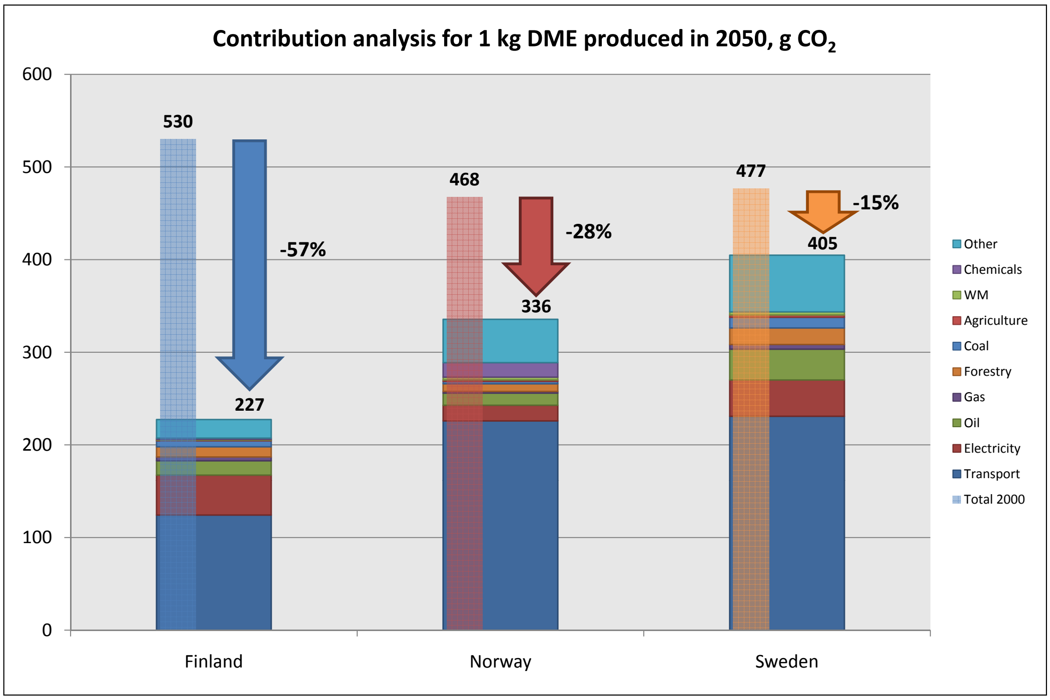


Figure 5.2: Reduction of unit-based emissions between 2000 and 2050 with scenario 2 (75% fuel substitution in 2050).

477 g) are domestically emitted in Sweden. In fact, North America, Asia, China and Middle-East are main exporters of oil products to Sweden; when one looks at the contribution of land transportation to the environmental impact of 1 kg DME (cf. figure 5.1), this trade pattern actually makes sense. This is even a stronger motivation for producing DME there, as Sweden (and the two other countries, to a lesser extent) would become independent from petroleum exporters, for the sake of energy security. Another interesting tool is the tier expansion analysis. This shows where the emissions occur along the successive steps of production. Figure 5.4 shows the accumulated emissions throughout the production feedbacks of one kilogramme of DME. As the final demand “calls” a sector from the foreground system, the first round only describes foreground production. Then, foreground processes call background processes, which, in turn, will call other sectors within the background economy etc. On this graph one can see that CO_2 emissions are mainly generated by background processes. Additionally, it is interesting to see that the curves are rocketing as soon as round 2, except for Sweden. This can be linked to the previous paragraph where one noticed that Sweden is more dependent on trade than the other countries: importing required commodities is obviously slower and demands more production rounds, than producing them domestically. Still, the fast increase of those curves shows that production of DME is not extensively industry-intensive as no important repercussions occur along the production round

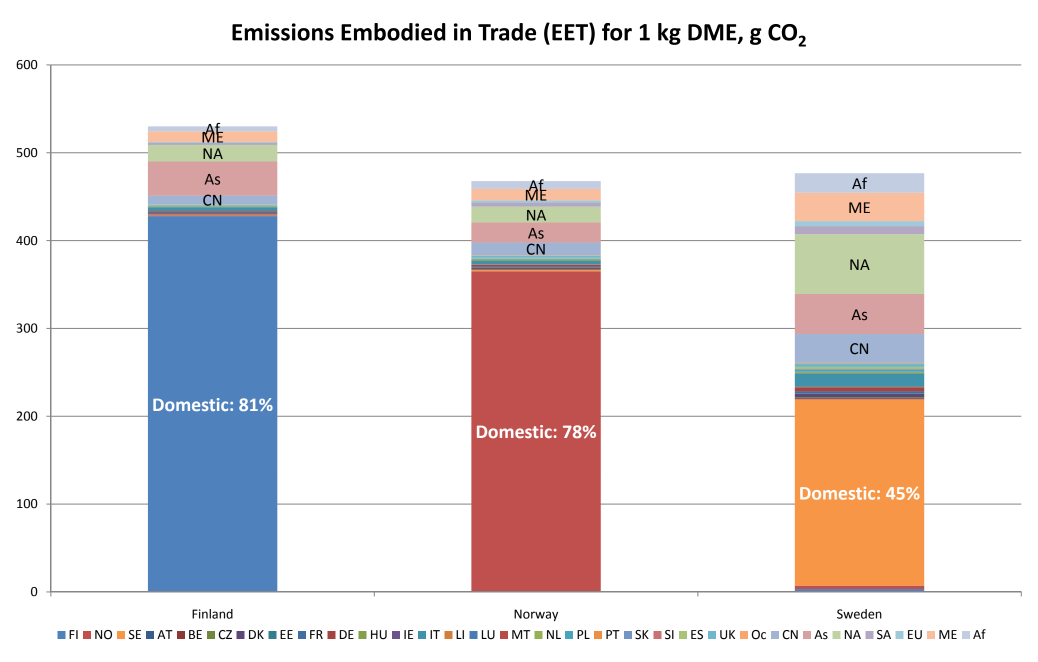


Figure 5.3: Emissions embodied in trade, for 1 kg DME produced in Finland, in Sweden and in Norway, at service station.

feedback loops. All in all, although Sweden presents a slightly different pattern in the way it deals with trade, this first section showed that the three countries are quite homogeneous and similar regarding their environmental profiles.

5.2 Scenario 1

The total output figures from the pulp and paper industry in Fenno-Scandinavia were key parameters in this scenario. One important remark should be raised: no emissions figures were calculated in this scenario, as the theoretical maximum production levels would be higher than what is required for meeting the domestic demands in motor fuel. Figure 5.5 shows how the production of DME can evolve over the upcoming decades according to a constant ratio $\frac{\text{pulp and paper output}}{\text{DME production}}$. The results for this scenario are crucial, as they set the theoretical maximum biofuel production levels from the best current technology available. In some sense, this scenario is therefore closely linked to the reality. Some adjustments have been made as, although black liquor was produced and recovered at a high rate in 2000, no commercial production of DME from this by-product took place in Fenno-Scandinavia. Consequently, the starting point is 0 Mt DME for year 2000 even though there is already a potential production because the raw material is available. In 2010 the production is 5% of the theoretical maximum (which is already an optimistic

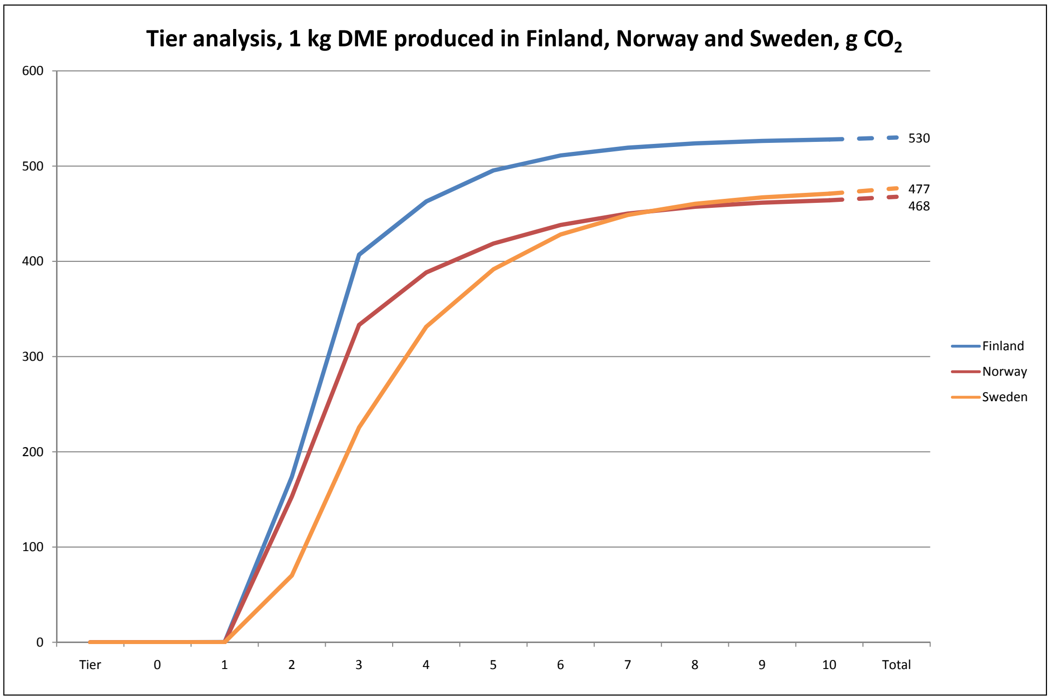


Figure 5.4: Tier expansion analysis for 1 kg of DME at service station.

assumption), taking into account a implementation period. From then on, it increases to reach half of the theoretical production in 2020 and from 2040 it is assumed that all the black liquor is recovered from pulp and paper plants, gasified and transformed into dimethyl ether. In 2050, 10.16 Mt are produced in Finland, 2.56 Mt are produced in Norway while Sweden refines 7.84 Mt. For the same year, the corresponding output from domestic pulp and paper industries is 54,141 M€ for Finland, 6,825 M€ for Norway and 37,049 M€ for Sweden. One might remark that this variable may be overestimated, as the demand in paper is likely to stagnate after a few decades, for out-of-scope reasons, such as the development of information technology and the inherent dematerialisation of telecommunication.

5.3 Scenario 2

This scenario yields very interesting results. Slowly increasing, but at a constant rate, the DME share in the fuel mix, results are really satisfying. Not very surprisingly, one can see that the share of DME in the fuel mix is definitely not directly linked to the cut-off in carbon dioxide emissions. In 2020, with a 9% substitution, the reduction of greenhouse gases emissions can reach 4.59 to 4.61 Mt in Fenno-Scandinavia, it corresponds to a -1.5% mitigation. This shows that with 75% of the total fuel supply substituted in 2050, as much as 12.8% of the total emissions in Fenno-Scandinavia can be saved, i.e. 70.3–70.5 Mt CO_2 equivalents subtracted

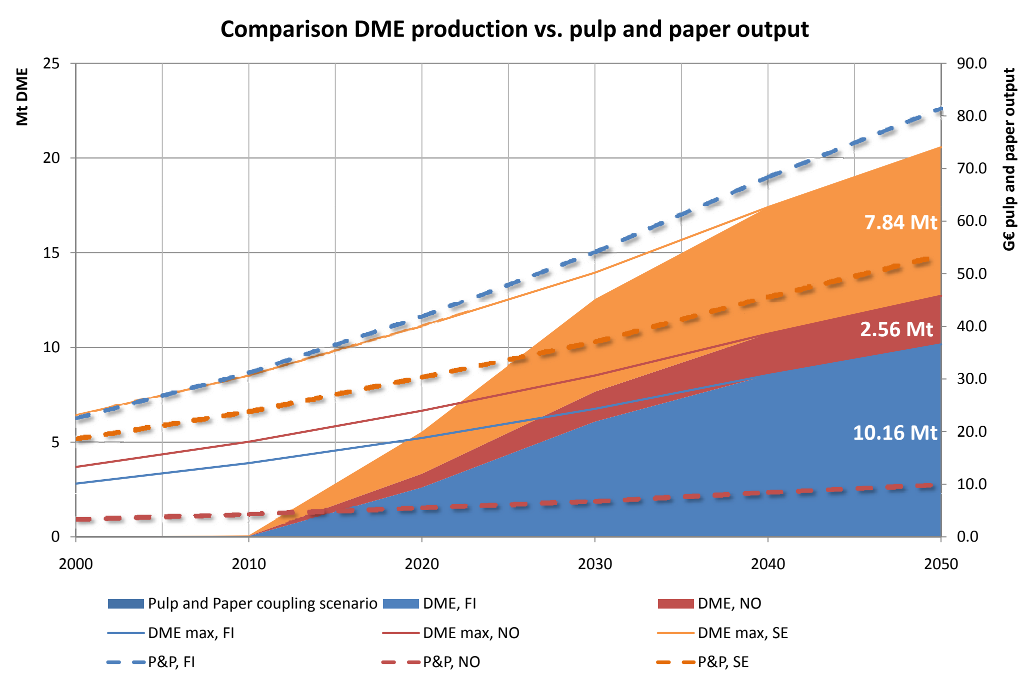


Figure 5.5: Parameters for the best-case scenario, coupling pulp and paper to DME production. Pulp and paper outputs are in billion € (G€) and not cumulated, while DME production is represented with cumulated areas, in Mt. The solid lines are the absolute maximum values, which obviously cannot be reached right away from 2000.

from the 551 Mt that would be emitted otherwise. The most important cutoff is the Finnish greenhouse gases reduction, the results show that 144.3 Mt CO_2 eq. would be emitted in 2050, instead of 184.0 in a context where biofuels are not produced in this country, i.e. nearly a 40 Mt mitigation. Notice that domestic substitution vs. total substitution does not make big differences, therefore for the rest of result presentation "scenario 2" will denote scenario 2a, with domestic substitution. From the year 2020 to 2040, the amount of greenhouse gases avoided gains one order of magnitude. A considerable increase of cut-offs is then apparently achievable, even though total annual emissions are not stable yet.

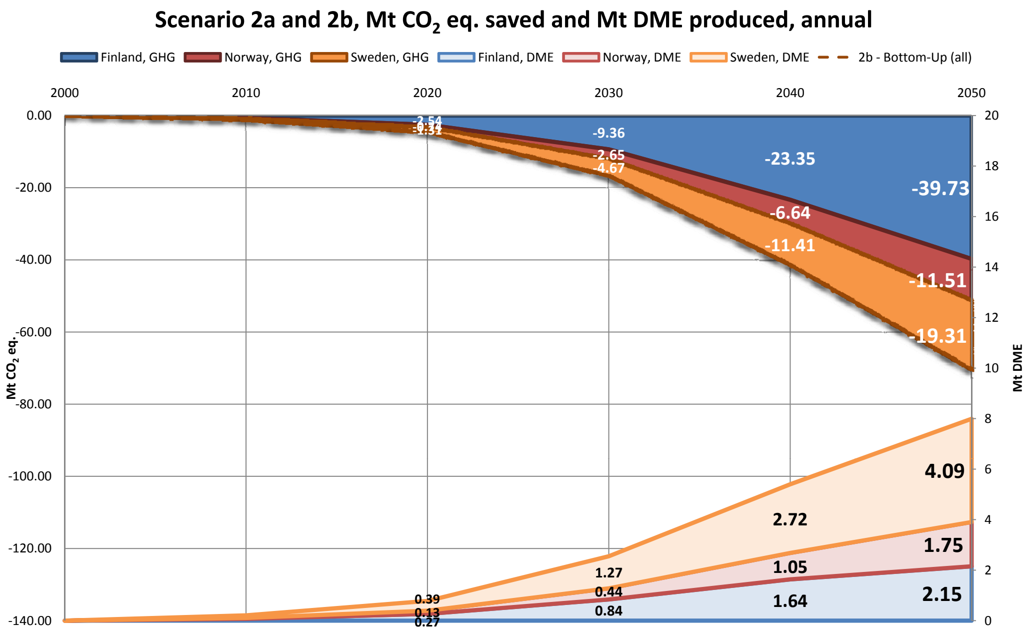


Figure 5.6: Results for Scenario 2. Mt CO_2 equivalents and Mt.

5.4 Scenario 3

Concerning the quantities of greenhouse gases emissions that would be avoided by 2050, they are 26.45 Mt CO_2 equivalents for Finland, 7.57–7.61 Mt CO_2 equivalents in Norway and 12.66–12.76 Mt CO_2 equivalents in Sweden. The most substantial savings are for Finland, where the only integration of biofuel production in pulp and paper mills would lead to a greenhouse gases mitigation of 21.6% compared to the baseline case. Regarding the way each sector contributes to GWP mitigation, one can give a glance at figure 5.8. This graph represents the variation in GHG emissions for the key-sectors in Fenno-Scandinavia between 2000 and 2050 due to an implementation of DME production according to scenario 3. Evidently, the only

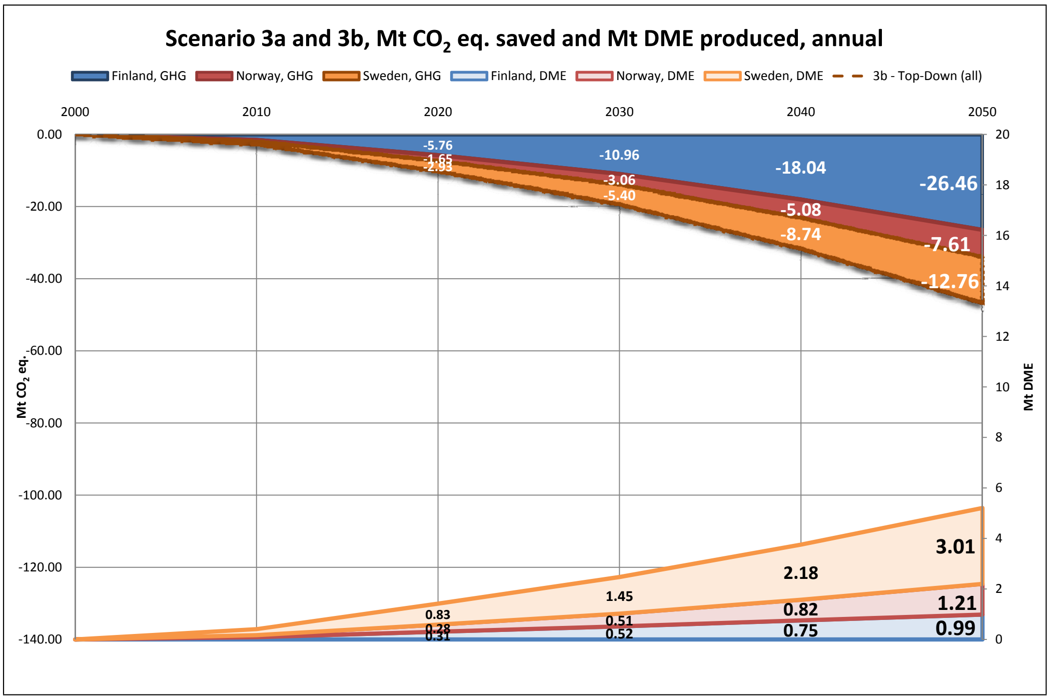


Figure 5.7: Results for Scenario 3. Mt CO_2 equivalents and Mt.

sector which experiences an increase is DME production, but this rise is very-well compensated by the key sectors using dimethyl ether. Agriculture, transportation and construction take conspicuous benefits from the utilisation of this biofuel with significant reductions of 4.99, 3.62 and 3.03 Mt in 2050, respectively. Forestry also takes advantage of DME but to a lesser extent, due to a lower fuel intensity, with 161 kt CO_2 equivalents avoided. Machinery, which is a very light sector, saves 16.2 kt CO_2 equivalents. These savings are proportional to the original share of fossil fuel which is an input to these sectors as well as their absolute weight in the national economy.

5.5 Comparison

A comparison of all the scenarios can be found in figure 5.9, regarding the cutoffs stimulated by each of them from 2000 to 2050. One can see in this figure the contribution of Finland, Norway and Sweden to the emissions of GHG in Fenno-Scandinavia, it should be noted that scenario 2 and 3 present the same relative ratio between those countries. This means that the shares presented on 5.9 which are for scenario 2, are actually valid both for scenarios 2 and 3. The overall savings in 2050 are 8.5% for scenario 3 and 12.9% for scenario 2, which is relatively obvious, since the emissions and the shares are closely related. However, as it has been mentioned the reduction differ from country to country. Under scenario 3 as-

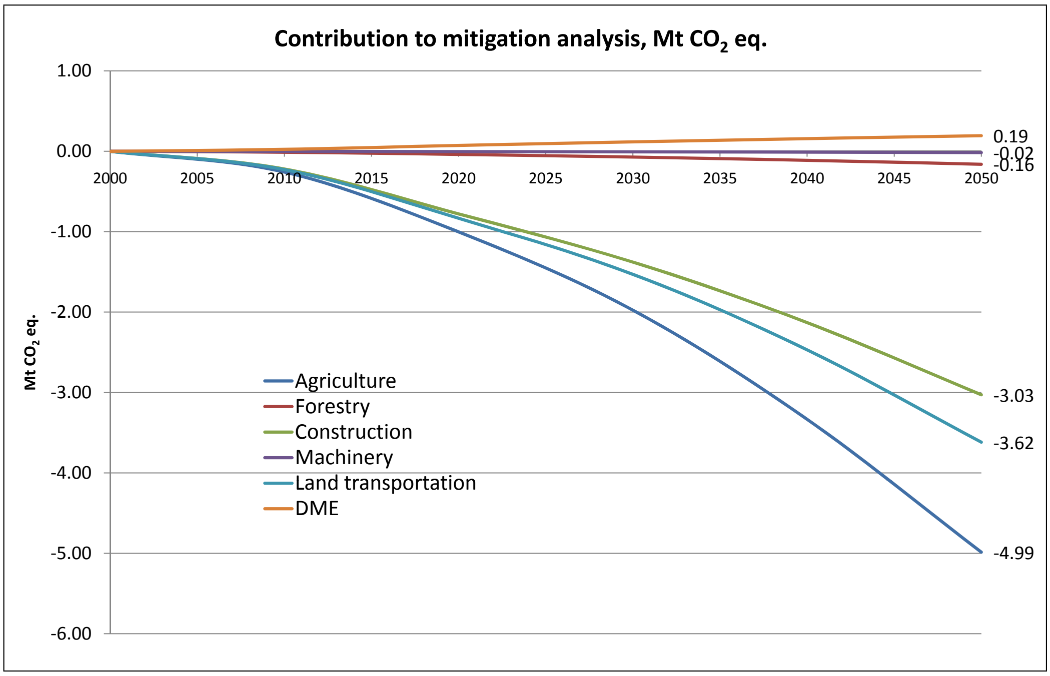


Figure 5.8: Contribution of each key-sector to greenhouse gases emissions mitigation in Fenno-Scandinavia, scenario 3.

sumptions, Finland avoids 14.4%, Norway 4.13% and Sweden 6.94% in 2050 while scenario 2 yields the following cut-offs: 21.6% for Finland, 6.25% for Norway and 10.5% for Sweden. There are also various ways, for the 3 countries, to contribute to this mitigation according to the scenario that has been followed. The output of DME is indeed different whether the demand is consumption-driven or technically-driven. For scenario 1, biofuel is produced according to the technical capacities of national production schemes, whereas scenarios 2 and 3 considered a demand induced by the substitution shares, then depending on national fuel consumption patterns. Figures 5.10b and 5.10a show the repartition of DME production in Fenno-Scandinavia in 2030. One can remark that high-capacity countries are not necessarily the ones which experience a high fuel demand. For instance, Finland almost produces half of the Fenno-Scandinavian dimethyl ether in scenario 1, while it produces a mere fifth of the total in scenario 2 and 3.

Finland has a better potential than Norway and Sweden, that use approximately the same share of their respective practical maximum production capacity. This can be seen on figure 5.11 where the Finnish share is remarkably low. In 2050, when all the pulp and paper mills are considered to be equipped with a DME production facility, Finland would only use 10 to 21% of this potential (according to the scenario) to satisfy the domestic demand. Figure 5.12 shows the absolute amount of dimethyl ether that can be produced in Fenno-Scandinavia, the darker shares are the shares that are actually required to meet the demand modelled in

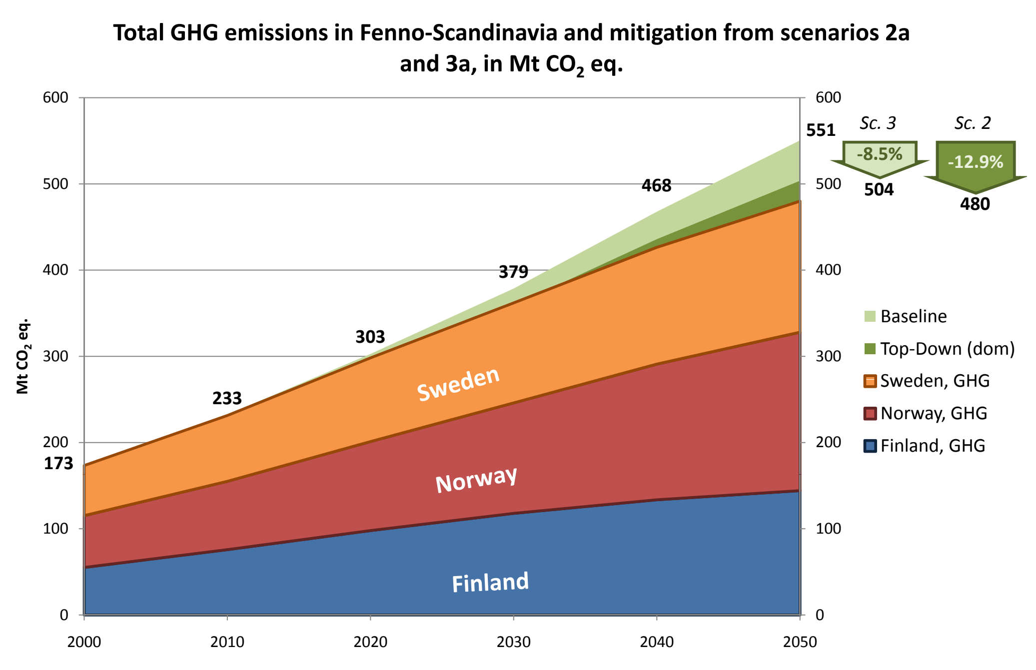
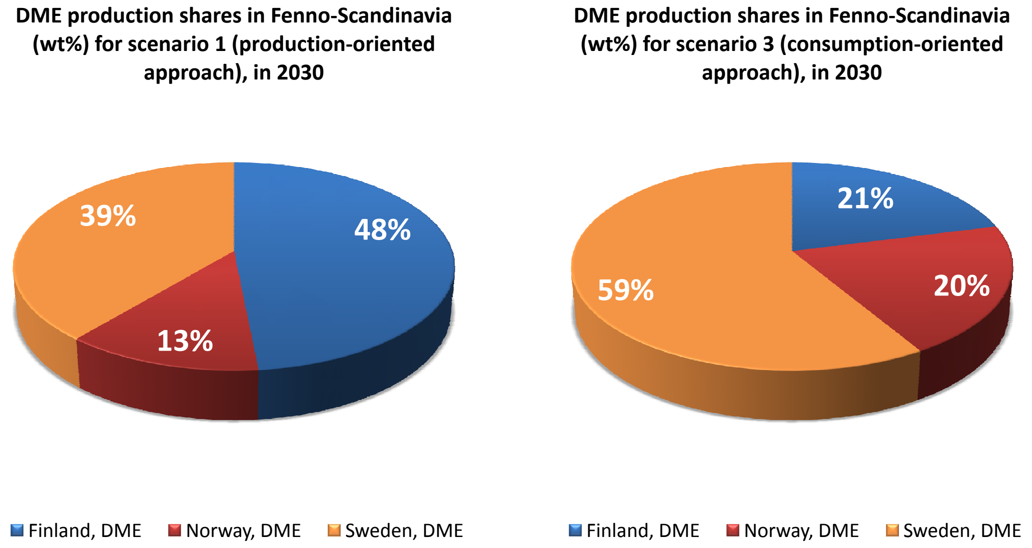


Figure 5.9: Comparison of scenarios: Baseline vs. bottom-up vs. top-down vs. pulp & paper coupling (theoretical maximum cut-offs).

scenario 2. Norway uses much of its limited capacity, while Sweden uses much of it as well, but has a larger surplus, in absolute terms. Last but not least, one can see that not only is Finland able to produce a large amount of DME from black liquor but it is also not consuming a substantial share of it, which makes it a high-potential country to that concern. Figure 5.12 presents the portion of maximum production capacity that countries are using to meet the requirements for scenario n° 2. The potential DME surpluses are shown in light color while the use for domestic supply is presented in darker shades. These results express the fact that Fenno-Scandinavia has a very high production capacity compared to what it can consume.



(a) Repartition of production, scenario 1.

(b) Repartition of production, scenarios 2 and 3.

Figure 5.10: Different production share distribution from country to country in Fenno-Scandinavia.

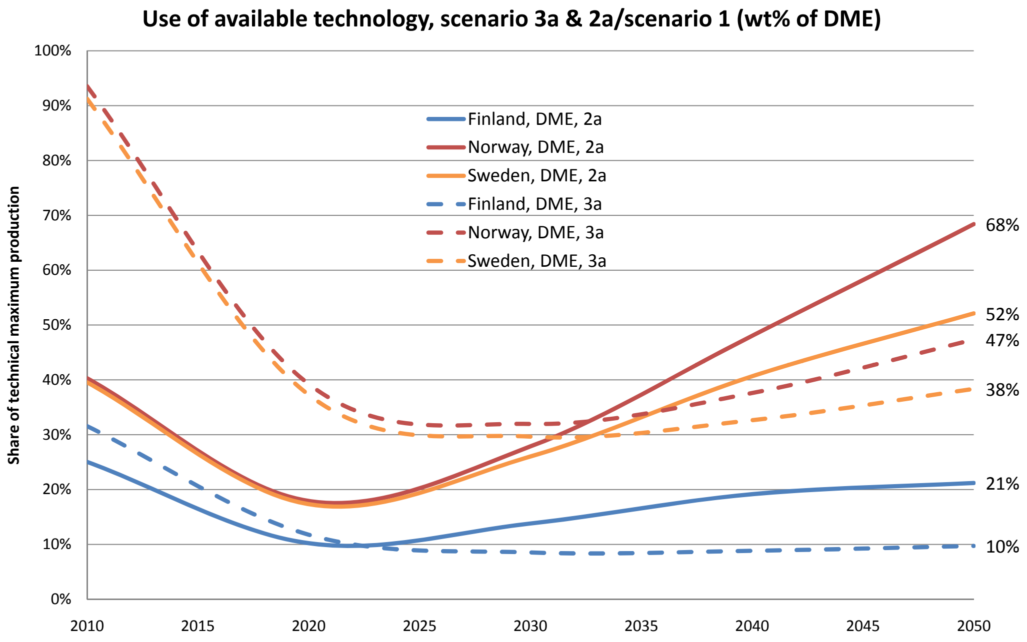


Figure 5.11: Use of maximum technology, relative, scenarios 2a and 3a.

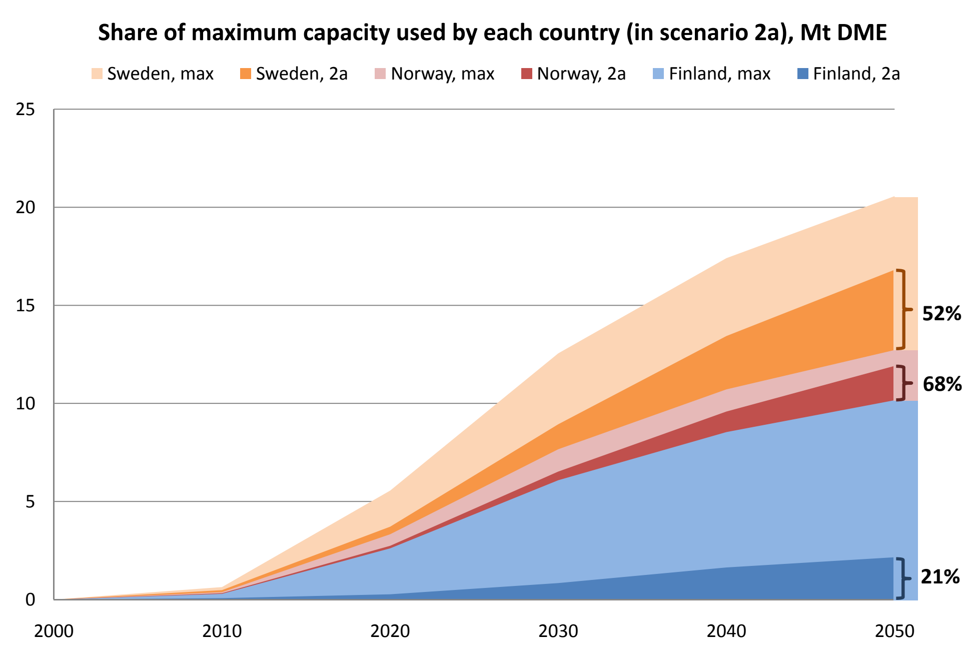


Figure 5.12: Use of maximum technology, absolute, scenario 2a.

Chapter 6

Discussion & Conclusions

Biofuels have been the object of a myriad of studies, and will surely be so for the upcoming decades. Today, the assessment of second generation biofuels is a mandatory stage when it comes to implementation projects. Given a very wide panel of opportunities (bioDME, biomethanol, FT-fuels or other BtL-fuels, etc.) and available technologies, it is of most concern to know how and to what degree our energy needs can be met through the biofuel option. In such assessment studies, it is also important to encompass a well-defined time and geographical scope, as there can be as many solutions as regions aiming at developing biofuel production.

The main goal of this study was to investigate the environmental impacts of a potential biofuel production scheme in Fenno-Scandinavia, using a powerful tool: a hybrid LCA/environmentally-extended input-output analysis framework. The biofuel that was examined is dimethyl ether produced from black liquor, a by-product from the pulp and paper industry. Several production scenarios have been analysed, coupled to a modelling of final demand. The per-unit and regional-sized results have raised interesting points that are to be discussed in the upcoming sections. Some primary objectives (reach a 20% cut-off by 2020 for instance) were rapidly considered as unrealistic and scenarios have been steered towards more feasible goals. Other more or less serious challenges have been encountered, raising difficulties. An exhaustive critique of this study is presented hereafter, mentioning limitations and propositions for future work. Finally, a summary of key findings will conclude this report, connecting the results to existing and potential policy.

Modelling future scenarios is by definition a tricky job. Obviously, the farther the time horizon, the more uncertainties can affect projections. For example, the demand has been modelled according to the gross domestic product of each country, but the consumption patterns may not be endlessly coupled to the GDP of a country as life standards have limits. This however relies on the basic principle that GDP and consumption are generally correlated. However, Guisan (2001) has performed an application "of the tests to the relation between private consumption and gross domestic product". Her results confirm that "cointegration tests fail very often to recognise causal relations", which means that at least this cointegration approach is not able to prove the correlation between consumption patterns and gross domestic product. Such challenges are really difficult to undertake, as consumption patterns obey to a plethora of unpredictable parameters.

Data quality is a very central issue in life cycle assessment and input-output analysis, as aggregation of *establishments* (in the acceptation of the United Nations (1999): *one* process for *one* product at *one* location) into economy sectors is unavoidable. Therefore, an obvious remark concerning further work on this topic would regard data quality and proper disaggregation. Challenges have been encountered all along the process of modelling and analysing how to disaggregate this or that sector, how to account for and distribute the flows that originally go to the other sector, etc. The price to pay is an exponentially increasing amount of data, there is no other option. Disaggregation has however been made in the most relevant sectors (forestry, biofuels, electricity) which is theoretically sufficient for the analysis. Generally, any model should be made as simple as possible but not simpler (according to Einstein (1934) this is even "the grand object of all theory"). This note about data quality and detail level especially concerns *price* quality. Contrarily to the assumption that has been made in this study, there is *one* price *per* sector-to-sector flow *per* year, and not only one price per year for each sector. Introducing a price matrix would unfortunately increase data intensity, but would be crucial for the robustness of results, as evoked by Suh (2004). This remark is important for goods that are used either by industries or households, as electricity or fuel, for which prices may vary a lot according to who the end user is. Prices are however not the only challenging consideration that are related to aggregation in this study. In fact, aggregation prevents from having a good insight about the quantity of fuel that can be substituted in some sectors. For instance, the land transportation sector does not actually embody only all kinds of road transportation but also "transport via pipeline". This can flaw the results if pipeline transportation is important (though it has been systematically assumed it is negligible). Consequently, DME is probably not used by absolutely all the activities within one aggregated sector.

Vice versa, vehicle motor fuels are not the only technology that would extensively use dimethyl ether. According to Nexant (2008), "promising fuel applications [of DME] include: LPG blending and substitute, diesel blending and substitute, power generation and acetylene substitute." This introduces further uses that are out of the scope of this study. Moreover, DME can also have medical applications: "The goals of treatment include the effective removal of warts without scarring (...) Nonprescription products may contain (...) a combination of dimethyl ether and propane" (Terrie, 2006) even though the probable share of DME dedicated to this purpose would be infinitesimal compared to its use as a motor fuel. Last but not least, the two primary commercial uses of this valuable biofuel are: as a propellant in aerosol canisters (as a substitute to chlorofluorocarbons, powerful greenhouse gases) and as a precursor to dimethyl sulphate. The company "Demeon"[1] produces DME industrially for these purposes mainly. A complete study should include all of these activities and final purposes. However, there is no doubt that the use of DME as a biofuel is dominating in terms of quantities in the wide panel of applications presented here.

Concerning the investigated stressors and impacts, only global warming potential has been analysed. This impact is the most important one regarding direct effects on climate change and biodiversity concerns. All policies about emission mitigation generally address global warming, because it is fairly easy and accurate to assess, and does not introduce many uncertainties. Global warming is also the first anthropogenic impact that should be tackled, being the most threatening effect within the panel of environmental impacts (acidification, eutrophication, toxicity potentials...). One must acknowledge that enormous uncertainties may be introduced with the assessment of biofuels. De Santi *et al.* (2008) have found a variation of more than 10,000% in N_2O emissions among a representative set of cultivated lands in Europe. However, it should also be noticed that the present system does not have substantial inputs from agriculture (see figure 5.1), contrarily to a large number of biofuels for which this is of most concern (Gibon, 2008). Therefore, eutrophication or photochemical oxidation have not been considered in this study.

Another point that should be raised is the fast multiplication of biofuel production technologies. DME from black liquor is just a small tree in the forest of all possible ways to benefit from lignocellulosic feedstocks to produce biofuels. This especially considering that even though DME production may be a panacea in Fenno-Scandinavian countries, it may still be totally inefficient in the rest of Europe. As a consequence, it would have been of most interest to address many more technologies in this study, including *other sectors* than the fuel industry and, additionally, *other countries.* Representing 2/3 (i.e. 282 PJ (Ekbom *et al.*, 2005)) of the European black liquor production but only 2.4% of the European population, Finland and Sweden are exceptions, definitely.

Trade schemes should definitely be investigated. Results show that Finland (and Sweden, to a lesser extent) has an enormous potential for the production of dimethyl ether. It is likely that the surplus between total capacity and what is stimulated from domestic industries could be displaced to substitute other countries' fuel. Additionally, it can be done through very slight changes in the model, although a feedback process should be implemented. The process would calculate for every decade what share of DME could be traded between Fenno-Scandinavian countries. An application of the World Trade Model such as developed by Duchin (2005); Strømman & Duchin (2006) could perfectly be considered, for instance. Trading issues bring us to the most important lack of this study: economical assessment. In fact, few people (this term encompasses industry decision-makers as well as final consumers) will accept to shift their fuel consumption towards biofuel if there is no economical benefit. Pollution tax schemes are one solution. Developed and developing countries' governments should take the decision to implement

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[1] `http://www.demeon.com`

a carbon tax on fossil fuels in a systematic way, in order to make biofuels more competitive to the fossil fuel market. Finland was the first country in Europe to put this plan into action, rapidly followed by Sweden and Norway in the 1990's. This makes the results of this study more realistic because dimethyl ether is likely to become a serious competitor on the fossil fuel market. Some bottlenecks may appear after the implementation of such taxes. For example Jagers & Hammar (2009) have conducted an interesting survey about the unpopularity of carbon tax in Sweden. This tax has been implemented there in 1991, as of 2009 its value is 0.4€ per litre of fossil fuels. They conclude that avoiding this tax instrument would make it legitimate in the eyes of the Swedish citizens. The direct consequence for the development of DME is a constraint on its price: should government subsidies to pulp mills which would choose to turn themselves into biorefineries be envisaged, instead of taxes on fossil fuels? Reduction of greenhouse gases emissions and oil use is too much of a challenge to be undertaken by an isolated action. Such a potential solution should be handled with care and accompanied by a set of decisions and actions by other parties. The acceptance of policies and the evolution of collective conscience is discussed later in this section.

Considering the realism of scenarios, they all imply slight technology changes in nations' fleets of cars and heavy duty vehicles. However, as dimethyl ether is similar to liquefied petroleum gas, LPG distribution could be used without problem (Petterson, 2006) in the three countries for DME. Technology changes in the car industry have not been taken into account, but given that the lifetime of any car is shorter than the time scope of this study, a slow change in car manufacturing can be imagined. A proper analysis would however have considered adjustments in the "Manufacture of motor vehicles, trailers and semi-trailers" vector within the A-matrices. Regarding processes further upstream in the value-chain, the production of DME seems realistic as serious experiments have been conducted, and very thorough reports such as Ekbom *et al.* (2003) tackle all the practical challenges to the implementation of DME from black liquor biorefineries in pulp mills.

The production of biofuel has a strong advantage: it can be developed in any place, in any context, given that many raw materials match the requirements for being utilised as feedstock for first- and second-generation biofuels. This statement is even truer for the last category, as lignocellulose is an "abundant and diverse" feedstock (Wikipedia, 2009). Using a by-product is an advantage for DME from black liquor, as usual second-generation biofuels use "fresh" lignocellulosic feedstocks and then have a bigger impact on land use, fertilising, and other collateral agricultural impacts. These concerns indeed are the most frequent critics that biofuel receive. However, this industrial activity often requires high energy inputs, mainly through electricity and transportation. In this study, both sectors represent 62.6–78.9% of the total emissions released for the production of dimethyl ether from black liquor. Even though the final product is exactly the same, national economies can be very different, and are then imputable for discrepancies on per-unit impact assessments: while 1 kg DME produced in Finland is responsible for 530 g CO_2, 1 kg of Norwegian DME is only chargeable for 468 g in 2000. These per-unit results were compared to the results from an LCA addressing the same foreground system, and it appeared that Input-Output analysis clearly encompasses more processes. With broader system boundaries, it has been found that the variation in embodied CO_2 is -0.2% to +13%. Since this variation changes rapidly along the decades it would be interesting to perform an LCA of the same product in 2050 in order to compare with input-output results for the same year.

On a regional scale, these results have an important leverage. It is interesting to notice that the most promising countries are Finland and Sweden, regarding both the potential production levels and the environmental performances. A point to keep in mind is that no less than *two thirds* of the whole black liquor production in entire Europe takes place in Finland and Sweden. Although per-unit results are excellent for Norway, its limited capacity in terms of "resource" (black liquor) cannot compete with the most influential countries in the global pulp and paper industry. The other penalising fact for Norway is the quantity of fuel supplied to the group of industries considered in the study. The best-case scenario shows that more than 20.6 Mt of DME could be injected in the Fenno-Scandinavian fuel mix by 2050, including one half from Finland. Glancing at results from scenario 2 and 3, one can notice that Norway utilises an important share of its maximum production levels very quickly, due to a limited capacity and a substantial fuel demand. Nonetheless, Finland, thanks to a well-developed pulp and paper industry and a low fuel demand has an enormous potential for producing DME. Moreover, figure 5.2 shows that Finnish industries benefit so much from the use of this biofuel that it has major repercussions on the production of dimethyl ether from black liquor itself. The link between DME production and pulp and paper industry output is illustrated by figure 5.5 where one can see the obvious gap between Norway and the other countries. In that sense, results are really encouraging for countries that are already world-class actors in the pulp and paper industry.

Bright (2008) and Statens forurensningstilsyn (2007) have investigated other wood-based biofuel production scenarios in Norway. Among other options, they study the potential environmental gains of BtL in Norway. They find that 1.36 Mt (Bright, 2008) and 1.4 Mt (Statens forurensningstilsyn, 2007) of CO_2 could be saved by 2020, with a 20% share of BtL-fuel in the national fuel mix. This study shows a reduction of 1.65 Mt under the same conditions but with a different biofuel. This difference (18%) can be justified: DME from black liquor is made from a by-product, and does not exist *per se* but only because of pulp and paper industry. Allocation factors make pulp and paper (main products) responsible for the major share of emissions during the paper fabrication process.

To sum up, recovering black liquor to produce DME offers notable performances for several reasons. Certainly, resources for this production scheme are limited as it relies on the pulp and paper industry. As Bright (2008) stipulates, there is no "silver bullet" with biofuels. It would nevertheless be very interesting to assess this technology within a context of total dematerialisation; in other terms, the development of such a biofuel would be a top choice in an economy obeying the principles of industrial ecology. Assessing DME's environmental performances in the current context is the equivalent of criticising the low efficiency of a lumberjack regardless of the fact that he has to use an old rusted axe since he cannot afford a chain saw. Biofuels have a high potential, but they cannot fully express it in our current fossil-dependent and carbon-generating economies. Nevertheless, there is a deep paradox in this concept, as sectors need every other sector to meet each other's demand in a *comme il faut* way, one of them has to take the initiative of becoming "green", leading each other towards the same goal. This is well-illustrated by some results of this study: if key sectors started to buy and use biofuels (*via* efficient policies, government subsidies, carbon taxes and so on) they would have a smaller carbon footprint. The biofuel industry would in turn acquire better environmental performances, which makes the rest of the industries that consume fuel "greener" and so on. This infinity of feedback loops has a stable limit that cannot be better mathematically expressed than by the Leontief inverse, $L = (I - A)^{-1}$. This multi-industrial issue is addressed in the chapter "Mitigation from a cross-sectoral perspective" in the IPCC Fourth Assessment Report (WG III) where it is clearly stated that "No one sector or technology can address the entire mitigation challenge" (Barker *et al.*, 2007).

If climate change mitigation is one main aspect of the reasons why biofuel production should seriously be addressed, energy security is the other main one. In fact, scientists and politicians agree on the imminence of a *peak-oil* phenomenon, after which petroleum production will decrease due to the fast depletion of crude oil in world reserves and fossil fuel will become unaffordable for common use. A report named "State of the World 2005" states that 33 of the 48 largest oil-producing countries had already reached this point in 2005 and now experience a declining production of crude oil (WorldWatch Institute, 2005). This could have severe implications in geopolitics and diplomatic relationships. In 2007, in his annual "State of the Union" address, US president Bush stated that "For too long, our Nation has been dependent on oil. America's dependence leaves us more vulnerable to hostile regimes, and to terrorists" (The White House, 2007), which stresses on the increasing urgency to develop energy independence in fuel-consuming countries. Local production of fuel is the key, if Finland and Sweden could encourage a nation-wide biofuel production scheme (Norway's energy security is ensured for a longer time scope by oil reserves in the North Sea), they would not depend on any other country (cf. figure 5.3) for their fuel supply and reduce further risks of diplomatic incidents with the OPEC countries. Implications of peak oil have been investigated in a study by Kerschner & Hubacek (2008) where the authors use input-output to analyse the consequence of this grave phenomenon on importing and exporting countries' economies. They argue that assuming a total elasticity of all the sectors within a demand-driven model is too optimistic as constraints have to be modelled for some sectors, notably oil extraction and refining. With constant technology coefficients, it can be found that transportation would be badly touched by the peak-oil phenomenon, while Kerschner & Hubacek (2008)'s model prove that other sectors are much more affected.

Policies have nevertheless already been proposed within the highest spheres of worldwide authorities: in Europe (Europa, 2007a,b), in the United States (The White House, 2007) and Japan (The Ministry of Economy, Trade and Industry, 2008). The differences in these policies' guidelines deserve attention: while Europe and the US only deal with the fuel sector itself, which after all is the main responsible for the emissions of greenhouse gases, Japan plans a total integrated approach to mitigation. It is really interesting to see that this approach involves changes in "automobiles, fuel and infrastructure" and that it mentions 2050 as a deadline to cut 50% of the emissions. As of 2009, only Japan directly addresses deep technological and behavioural changes. The two other members of this *triumvirate* should definitely consider similar actions. This is because it is only through a total implication of primary, secondary and tertiary sectors as well as households that the problem could be durably solved. According to Suzuki (2007), even straightforward but appropriate measures could be more effective than a simple infusion of biofuels in national economies if they were applied first: "biofuels alone are not the quick-fix answer to global warming. In fact, strong legislated policies to improve the efficiency of our cars, homes and industries is a much more effective strategy". In other words, not only would the biofuel sector have difficulties solving the climate challenge without the implication of other industries, but its effects are also critically mitigated if the collective conscience is not encouraged to shift towards more environmentally-friendly thinking through appropriate policies. Economic implications should also be addressed in a dedicated manner. Since consumers would never decide to change anything about their way of life if they had to invest more money to obtain the same commodities, and since industry output is led by consumption ($x = Ly$) incentives should be developed from consumers' perspectives. To a broader extent, education has definitely a role to play in this context. Nothing can be done if the populations of the developed countries (and of the developing countries on a longer term) do not acquire the necessary awareness regarding environmental issues. Time has come to change our mind, technology can help us to head towards a more sustainable future, only if we consider changing as well. A French Renaissance writer, François Rabelais, once wrote: "Science without conscience is but the ruin of the soul" (Rabelais, 1532). It was in the XVI$^{\text{th}}$ century.

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Appendix A

Taylor series tier expansion

The whole chapter was adapted from Steen-Olsen (in writing). The total production, and hence the total emissions, occurring in each *tier* of production can be analysed using a series expansion. Starting from the fundamental assumption of LCA, that the total output due to an exogenous final demand equals the final demand itself plus the inter-industrial required inputs to produce the total output:

$$x = A * x + y \tag{A.1}$$

By substitution and re-substitution this can be infinitely expanded as follows:

$$\begin{aligned}
&x = A(A * x + y) + y = A^2 * x + A * y + y = (I + A) * y + A^2 * x \\
&x = A^2 * (A * x + y) + A * y + y = A^3 * x + A^2 * y + A * y + y = (I + A + A^2) * y + A^3 * x \\
&\vdots \\
&x = (I + A + A^2 + A^3 + \ldots + A^s) * y + A^{s+1} * x
\end{aligned} \tag{A.2}$$

In a life cycle assessment, the technical coefficient matrix A is generally assumed to contain only positive elements less than or equal to 1. As such, we expect the term $A^{s+1}x$ to approach zero as s grows large. The total output x can then be expressed as a function of A and Y:

$$x = \lim_{s \to \infty} (I + A + A^2 + A^3 + \ldots + A^s) * y \tag{A.3}$$

By studying equation A.3, it can be shown that each of its term actually describe one production tier. The first term, Y, is simply the final demand itself, which is the immediate production requirements from the final demand. The next term, $A * y$, is the additional production needed to produce the inputs that go to produce the final demand. The third term, in turn, is the additional production needed to produce those inputs, and so on. Schematically, this can be shown as follows:

$$\begin{array}{lll} \text{Tier 0:} & x_0 = & y \\ \text{Tier 1:} & x_1 = & A * y \\ \text{Tier 2:} & x_2 = & A^2 * y = A * x_1 \\ \text{Tier 3:} & x_3 = & A^3 * y = A * x_2 \\ \text{Tier 4:} & x_4 = & A^4 * y = A * x_3 \\ \vdots & \vdots & \vdots \\ \text{Tier } s\text{:} & x_s = & A^s * y = A * x_{s-1} \end{array} \tag{A.4}$$

Notice that the output in each tier equals the requirements matrix A times the output of the previous tier. The total output, then, is the sum of all the individual tier outputs:

$$x = \lim_{s \to \infty} \sum_{t=0}^{s} x_t = \lim_{s \to \infty} (I + A + A^2 + A^3 + \ldots + A^s) * y \tag{A.5}$$

which is the same result obtained in equation A.3

Appendix B

NACE and extra sectors

This is a list presenting the 78 sectors that have been used to model the economy of 23 European countries. The background system was gathered from Eurostat (2009), then the NACE classification was used to describe 59 sectors. For those sectors, the original correspondence number in the NACE classification is specified in parentheses. Note that electricity sector has been disaggregated, then 64 sectors are in the background system.

- 14 extra sectors, foreground system:

    1. Roundwood,
    2. Wood chips,
    3. Wood waste,
    4. Transportation,
    5. Fuel synthesis plant/p/RER/I U (p),
    6. Dimethyl ether synthesis, black liquor/h/Chemrec U,
    7. Gas cleaning, black liquor/h/Chemrec U,
    8. Autothermal entrained flow gasification, black liquor/h/Chemrec U,
    9. process specific emissions, conversion plant/RER U,
    10. Refinery gas, burned in flare/GLO U,
    11. Heat, biomass, at steam and power boiler/MJ/Chemrec U,
    12. Electricity from DME facility,
    13. Dimethyl ether, black liquor, at synthesis plant/kg/Chemrec U,
    14. Dimethyl ether, black liquor, at service station/kg/Chemrec U.

- 64 sectors, NACE classification, background system:

    1. Agriculture, hunting and related service activities (01),

2. Forestry, logging and related service activities (02),
3. Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05),
4. Mining of coal and lignite; extraction of peat (10),
5. Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying (11),
6. Mining of uranium and thorium ores (12),
7. Mining of metal ores (13),
8. Other mining and quarrying (14),
9. Manufacture of food products and beverages (15),
10. Manufacture of tobacco products (16),
11. Manufacture of textiles (17),
12. Manufacture of wearing apparel; dressing and dyeing of fur (18),
13. Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19),
14. Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20),
15. Manufacture of pulp, paper and paper products (21),
16. Publishing, printing and reproduction of recorded media (22),
17. Manufacture of coke, refined petroleum products and nuclear fuels (23),
18. Manufacture of chemicals and chemical products (24),
19. Manufacture of rubber and plastic products (25),
20. Manufacture of other non-metallic mineral products (26),
21. Manufacture of basic metals (27),
22. Manufacture of fabricated metal products, except machinery and equipment (28),
23. Manufacture of machinery and equipment n.e.c. (29),
24. Manufacture of office machinery and computers (30),
25. Manufacture of electrical machinery and apparatus n.e.c. (31),
26. Manufacture of radio, television and communication equipment and apparatus (32),
27. Manufacture of medical, precision and optical instruments, watches and clocks (33),
28. Manufacture of motor vehicles, trailers and semi-trailers (34),
29. Manufacture of other transport equipment (35),
30. Manufacture of furniture; manufacturing n.e.c. (36),

31. Recycling (37),
32. Electricity from hard coal; gas, steam and hot water from coal,
33. Electricity from nuclear power,
34. Electricity from natural gas,
35. Electricity from petroleum and nec,
36. Electricity from hydro,
37. Electricity from wind,
38. Collection, purification and distribution of water (41),
39. Construction (45),
40. Sale, maintenance and repair of motor vehicles and motorcycles; retail sale services of automotive fuel (50),
41. Wholesale trade and commission trade, except of motor vehicles and motorcycles (51),
42. Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52),
43. Hotels and restaurants (55),
44. Land transport; transport via pipelines (60),
45. Water transport (61),
46. Air transport (62),
47. Supporting and auxiliary transport activities; activities of travel agencies (63),
48. Post and telecommunications (64),
49. Financial intermediation, except insurance and pension funding (65),
50. Insurance and pension funding, except compulsory social security (66),
51. Activities auxiliary to financial intermediation (67),
52. Real estate activities (70),
53. Renting of machinery and equipment without operator and of personal and household goods (71),
54. Computer and related activities (72),
55. Research and development (73),
56. Other business activities (74),
57. Public administration and defence; compulsory social security (75),
58. Education (80),
59. Health and social work (85),
60. Sewage and refuse disposal, sanitation and similar activities (90),

61. Activities of membership organisation n.e.c. (91),
62. Recreational, cultural and sporting activities (92),
63. Other service activities (93),
64. Private households with employed persons (95).

Appendix C

Electricity mixes

Electricity mixes for all 31 regions are showed in table C.1 below. The sources used are electricity output data from Eurostat (2009) and the International Energy Agency (2009).

Electricity mixes for the aggregated regions were estimated from the electricity mixes of the largest countries of the region, and scaled to match actual populations. For each aggregated region, the countries used were:

- **Oceania**: Australia, New Zealand
- **Asia**: India, Indonesia, Pakistan, Bangladesh, Russia, Japan
- **North America**: USA, Mexico, Canada
- **South America**: Brazil, Colombia, Argentina
- **Rest of Europe**: Bulgaria, Croatia, Cyprus, Greece, Iceland, Latvia, Romania, Switzerland
- **Middle Eas**t: Turkey, Iran, Iraq, Saudi Arabia
- **Africa**: Nigeria, Ethiopia, Egypt, D.R. Congo, South Africa

Table C.1: Electricity mixes assumed for all modeled regions. All values in percent of region's total electricity production.

Region	**Hard coal**	**Nuclear**	**Natural Gas**	**Oil**	**Hydro**	**Wind**
Austria	7.7	0.0	13.5	3.0	75.7	0.1
Belgium	16.2	60.5	20.1	1.0	2.1	0.0
Czech Republic	22.1	54.5	12.6	1.5	9.3	0.0
Denmark	48.8	0.0	25.7	13.0	0.1	12.4
Estonia	0.0	0.0	92.3	6.9	0.6	0.1
Finland	15.1	39.8	17.9	1.1	26.0	0.1
France	5.1	77.9	2.1	1.3	13.6	0.0
Germany	35.3	41.8	13.0	1.2	6.4	2.3
Hungary	0.3	55.7	26.0	17.3	0.7	0.0
Ireland	30.8	0.0	41.8	21.1	5.2	1.1
Italy	9.8	0.0	38.3	32.4	19.2	0.2
Lithuania	0.0	74.3	14.3	5.8	5.7	0.0
Luxembourg	0.0	0.0	20.8	0.0	76.8	2.4
Malta	0.0	0.0	0.0	100.0	0.0	0.0
Netherlands	27.4	4.8	62.8	3.8	0.2	1.0
Norway	0.0	0.0	0.1	0.0	99.8	0.0
Poland	92.2	0.0	1.0	2.1	4.6	0.0
Portugal	34.7	0.0	17.0	20.0	27.9	0.4
Slovakia	11.9	58.0	11.9	0.7	17.5	0.0
Slovenia	3.3	51.5	3.2	0.6	41.4	0.0
Spain	33.8	28.9	9.8	10.5	14.8	2.2
Sweden	1.2	40.9	0.3	1.2	56.1	0.3
United Kingdom	32.4	23.0	40.0	2.3	2.1	0.3
Oceania	70.7	0.0	14.0	0.8	13.7	0.8
China	80.4	1.9	0.5	1.8	15.2	0.1
Asia	34.2	15.7	27.8	8.0	14.0	0.3
North America	44.8	18.3	19.5	2.8	13.9	0.6
South America	2.9	3.8	14.5	3.6	75.2	0.1
Rest of Europe	2.9	29.6	12.0	10.8	44.4	0.3
Middle East	0.6	0.0	55.8	33.7	9.9	0.0
Africa	58.5	2.9	24.0	5.1	9.3	0.2

Appendix D

GDP annual changes

This table presents the figures that have been used to model the net final demand vectors along the decades. It is based on two sources, which publications are separated by a two-year interval: Mantzos & Capros (2006) and Capros *et al.* (2008). All these annual variations were calculated using the *PRIMES* model. For later decades, only the Finnish, Norwegian and Swedish GDP increases were estimated, the other countries keeping the same increase as on 2030.

Table D.1: GDP change, in % per year.

Country/region	2000 to 2010	2010 to 2020	2020 to 2030
Austria	2.0	1.9	1.4
Belgium	1.9	1.9	1.5
Czech Republic	4.1	3.6	2.4
Denmark	1.9	1.8	1.3
Estonia	8.1	3.8	2.4
Finland	2.8	1.9	1.4
France	1.9	2.4	1.8
Germany	1.3	1.7	1.1
Hungary	3.8	3.5	2.7
Ireland	5.0	3.5	2.5
Italy	1.2	1.9	1.5
Lithuania	7.1	4.7	3.8
Luxembourg	3.8	3.4	2.6
Malta	1.4	3.7	2.8
Netherlands	2.0	1.9	1.5
Norway	2.2	2.4	1.9
Poland	3.7	4.6	3.3
Portugal	1.3	2.7	2.5
Slovakia	5.1	4.5	3.1
Slovenia	3.7	2.6	1.9
Spain	3.3	2.9	1.7
Sweden	2.8	2.3	1.8
United Kingdom	2.5	2.3	1.8
Oceania	3.5	2.5	2.2
China	7.2	4.9	4.1
Asia	5.5	4.5	4.0
North America	3.5	2.5	2.3
South America	3.8	2.9	2.8
Rest of Europe	2.5	2.1	1.8
Middle East	4.6	3.6	3.9
Africa	5.4	4.2	4.4

Appendix E

Matlab scripts

The software *MATLAB* (The MathWorks, 2008) was used both for the building of the multi-regional input-output framework and the scenario modelling. The code that has been produced for the whole first task is rather long and would not be very relevant to the comprehension of the results found in this study. Additionally, as several persons were involved in this project, this implies that the same operations could have been made in many different ways, making the code difficult to understand. Nonetheless, the script that has been typed for obtaining the results could give some insight about the way it has been processed.

```
clear all

%% Importing basic constructs
load A_adj.mat
load y_adj.mat
load s_unit_thomas.mat

%% Importing data
...not displayed...

%% Global parameters

% Characterisation matrix
C = [23,1000,296];

% Fenno-Scandinavian countries
scand_code = ['FI';'NO';'SE'];
scand_id   = [6,16,22];

% Model variables
s_EU_new   = 78;
s_EU_old   = 64;
s_ROW      = 62;
n_EU       = 23;
n_ROW      = 8;

% Number of extra sectors
extra      = s_EU_new-s_EU_old;

%% Scenarios parameters

% Sectors to replace
sectorDME    = 14;
sectoragr    = extra + 1;
sectorfor    = extra + 2;
sectorpaper  = extra + 15;
sectoroil    = extra + 17;
sectorconstr = extra + 39;
sectortrans  = extra + 44;
sectormac    = extra + 53;

% Share of fossils in each sector, used to know the
% maximum share that can be replaced in s
fossil = [...not displayed...];

%% Scenarios 2 and 3

% specific parameters

% shares in 2010, 2020 and 2030 in the diesel mix
DME_share(:,:,1) = [0.00,0.00,0.00,0.00,0.00;
                    0.00,0.00,0.00,0.00,0.00;
                    0.00,0.00,0.00,0.00,0.00]; % Baseline scenario
```

```
DME_share(:,:,2) = [0.03,0.09,0.26,0.52,0.75;
                    0.03,0.09,0.26,0.52,0.75;
                    0.03,0.09,0.26,0.52,0.75]; % Scenario 2
DME_share(:,:,3) = [0.07,0.20,0.30,0.40,0.50;
                    0.07,0.20,0.30,0.40,0.50;
                    0.07,0.20,0.30,0.40,0.50]; % Scenario 3

% Initial variables (domestic substitution assumption)
A_2000 = A_adj;
y_scen_2000 = y_2000;
s_2000 = s_unit_thomas;

%% Calculation

for i=1:5 % decades

    dec = num2str(10*i,'%02.0f');

    % Temporary variables
    s_t = s_unit_thomas;
    A_t = A_adj;

    % Naming new variables
    A_dec    = genvarname(['A_20',dec]);
    s_dec    = genvarname(['s_20',dec]);
    y_scen_dec = genvarname(['y_scen_20',dec]); % output y

    % Handling y
    eval(['y_t = y_20',dec,';']);
    eval([y_scen_dec,'= y_20',dec,';']);

    for p=1:3 % countries

        % Setting the indices for sectors which substitute fuel
        indsubst = s_EU_new*(scand_id(p)-1) +...
        [sectoragr,sectorfor,sectorconstr,sectortrans,sectormac];

        y_cols   = 4*(scand_id(p)-1)+1:4*(scand_id(p)-1)+4;

        % Diminishing oil
        A_t(s_EU_new*(scand_id(p)-1) + sectoroil,indsubst) = ...
    (1-DME_share(p,i,1)) * A_t(s_EU_new*(scand_id(p)-1) + sectoroil,indsubst);

        % Increasing DME
        A_t(s_EU_new*(scand_id(p)-1) + sectorDME,indsubst) = ...
    DME_share(p,i,1) * coef1(p) * A_t(s_EU_new*(scand_id(p)-1) + sectoroil,indsubst);

        % Adjusting s
        s_t(:,indsubst) = s_unit_thomas(:,indsubst) * ...
    diag(1 - DME_share(p,i,1) * fossil(p,:));

    eval([y_scen_dec,'(s_EU_new*(scand_id(p)-1) + sectoroil,y_cols) = ...
    (1-DME_share(p,i,1)) * y_20',dec,'(s_EU_new*(scand_id(p)-1) + sectoroil,y_cols);']);
```

```
    eval([y_scen_dec,'(s_EU_new*(scand_id(p)-1) + sectorDME,y_cols) = ...
    DME_share(p,i,1) * coef1(p) * y_20',dec,'(s_EU_new*(scand_id(p)-1) + sectoroil,y_cols);']);

    end

    % Storing temporary variables that have been adjusted
    eval([A_dec '= A_t;']);
    eval([s_dec '= s_t;']);

end

%% Getting x

I = eye(size(A_adj));

% "dom" stands for DOMestic assumption
for i=1:6
    dec = num2str(10*(i-1),'%02.0f');
    disp(['Decade 20',dec,'...'])
    L_dom_dec = genvarname(['L_dom_20',dec]);
    x_dom_dec = genvarname(['x_dom_20',dec]);
    eval([L_dom_dec,' = (I-A_20',dec,')^-1;'])
    eval([x_dom_dec,' = L_dom_20',dec,'* sum(y_scen_20',dec,',2);'])
end

%% Getting emissions and impacts
for i=1:6
    dec = num2str(10*(i-1),'%02.0f');
    disp(['Total emissions for decade 20',dec,'...'])
    E_dom_dec = genvarname(['E_dom_20',dec]);
    D_dom_dec = genvarname(['D_dom_20',dec]);
    D_pro_dom_dec = genvarname(['D_pro_dom_20',dec]);
    eval([E_dom_dec,' = s_20',dec,' * diag(x_dom_20',dec,');'])

    % Consumption-oriented impacts
    eval([D_pro_dom_dec,' = (C * s_20',dec,') * L_dom_20',dec,'* ...
    diag(sum(y_scen_20',dec,',2));']);

    % Production-oriented impacts
    eval([D_dom_dec,' = C * E_dom_20',dec,';'])
end
```