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Life Cycle Assessment of Offshore Wind Electricity Generation in Scandinavia

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Problem Description

The primary objective is to assess the life cycle environmental impacts of offshore wind power industry in Scandinavia, including both wind turbines and infrastructure for electricity transmission in the analysis. A hybrid life cycle assessment methodology should be applied to deal with the problems of incomplete system boundaries. Secondary objectives are: 1) To evaluate system designs and strategies for reducing the environmental impacts of offshore wind electricity generation; and 2) To evaluate the effects large-scale offshore wind power development in Scandinavia may have on different sectors of the economy, using input-output based modeling.
The analysis should include the following elements
1) Development of a basis MRIO database.
2) Compilation of hybrid life-cycle inventories for offshore wind energy systems. Inventories should be suitable for hybrid life cycle assessment and be adapted to Scandinavian conditions.
3) Compilation of data for Scandinavian countries in terms of resource potential, site specifications and suitable concepts for wind turbines and electricity transmission.
4) Development of scenarios for large-scale offshore wind power development in Scandinavia.
5) Assess the scenarios with respect to environmental as well as economic repercussions.
6) Discussion and analysis, including assessment of strategies for a sustainable offshore wind power industry in Scandinavia.

A complete description of the assignment text is given in document EPT-M-2009-72.

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

Preface

This thesis was written as the final part of my MSc degree at the programme of Energy and Environmental engineering, with a specialization in the programme of Industrial Ecology, at the Norwegian University of Science and Technology. Chapter 2 and section 5.1 to 5.4 of the thesis have been written in collaboration with four other master students at the Industrial Ecology Programme.

By writing this thesis I have been able to gain more knowledge about the offshore wind power situation in Scandinavia and Europe, as well as a deeper understanding of the environmental policies that are currently at stake. This has been highly interesting and educational for me. Even though the carrying out of the analysis may seem straight forward there has been a long way to walk in order to develop the system. At times the frustration has been big, but on the contrary; the triumph by getting the system to work has been even bigger.

I would like to thank my supervisors, Anders Hammer Strømman, Troy Hawkins and Anders Arvesen, for valuable guidance and support. Thanks also to the PhD students for helping us build the MRIO model. I also would like to give a big thank to my fellow students, Børge, Kjartan, Stian and Thomas, for the good collaboration throughout the process. The positive and inspiring atmosphere in the LCA laboratory has been a big motivation during the late night hours we have spent together working with this project. To my dear sister who proofread my report: Thank you so much! Last, but not least, I want to express my gratitude to my boyfriend, Jostein, who has not only backed me up when I needed it and helped me with proofreading, he has also been incredibly patient and supportive, and taken good care of me in stressful periods during the semester. Thank you!

Abstract

In this study a Multi Regional Input Output model has been developed for the base year 2000, and thereafter extended and hybridized to enable a study of offshore wind power generation in Scandinavia. Foremost the per-unit environmental impact of offshore wind power generation was calculated to an average of 16.5 grams of CO_2-eq. per kWh. The MRIO model offers a broad system boundary, covering a complete set of background flows and enables in this way a thorough study of the inter-regional value chains and the corresponding emissions embodied in trade.

Scenarios from 2000 to 2030 for future offshore wind power were developed on the basis of GDP projections and projections for future energy demand. One baseline scenario, assuming no further offshore wind power installation, was developed, together with a Medium and a High scenario of future offshore wind power installation. The installed wind power was assumed to replace non-renewable energy sources, primarily domestically and secondly in power importing countries. The Medium and High scenario resulted in a cumulative reduction of 220 Mtons CO_2-equivalents and 308 Mtons by 2030, respectively. The Norwegian offshore wind power was by a large exported, while Denmark and Sweden experienced a substantial wind power implementation into their economies, resulting in considerable increase in the percentage share of renewable energy in their electricity mix. This shows that offshore wind power could have a vital role in reaching the European Union's target of a 20% share of renewable energy by 2020, under the assumption that a substantial capacity of wind power is installed.

The results from this study provide important guidance and a broad overview of the effect a large wind power implementation will have on the Scandinavian economy.

Sammendrag

I dette arbeidet har en global multiregional kryssløpsanalysemodell (MRIO) for år 2000 blitt konstruert, og deretter utvidet og hybridisert for å muliggjøre en detaljert studie av miljøeffektene av offshore vindkraftutbygging i Skandinavia. Miljøeffekten av offshore vindenergi ble kvantifisert på enhetsbasis, til et gjennomsnittlig skandinavisk utslipp på 16.5 gram CO_2-ekvivalenter per kWh produserte vindenergi. MRIO-modellen tilbydde en fullstendig systemgrense, i tillegg til at den muliggjorde en grundig studie av inter-regionale verdikjeder, inkludert kvantifisering av utslipp inkorporert i import.

Scenarioer fra 2000 til 2030 ble utviklet på grunnlag av BNP-framskrivinger og framskrivinger for energibruk. Tre scenarioer ble simulert; et basisscenario uten antagelse om noen fremtidig vindkraftutbygging, samt et medium og ett høyt scenario for fremtidig vindkraftutbygging. Installert vindkraft var antatt å erstatte elektrisitet fra ikke-fornybare energikilder først innenlands og deretter i eventuelle importerende land. Medium og Høyt scenario resulterte i en kumulativ utslippsreduksjon på hhv. 220 Megatonn og 308 Megatonn CO_2-ekvivalenter fram mot 2030. Den norske vindkraften ble i hovedsak eksportert, mens Danmark og Sverige opplevde en betydelig vindkraftimplementering i sine energisystemer, som resulterte i betraktelige økninger i prosentandel fornybar energi i elektrisitetsmiksen. Dette indikerer at offshore vindkraft kan spille en vesentlig rolle når det gjelder å nå EUs mål om 20 % fornybar energi før 2020, avhengig av at betydelige vindkraftutbygginger gjennomføres.

Resultatene fra dette arbeidet skaffer viktige indikasjoner samt en bred helhetsoversikt over hvilke miljøeffekter en større vindkraftutbygging i Norden vil medføre.

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Abbreviations

AP	Acidification potential
CH_4	Methane
CO	Carbon monoxide, fossil
CO_2-eq.	Carbon dioxide equivalents
EEA	European Environment Agency
EEC	Emissions Embodied in Consumption
EEE	Emission Embodied in Exports
EEI	Emission Embodied in Imports
EEIOA	Environmentally Extended Input-Output Analysis
EEIO-LCA	Environmentally extended input-output Life Cycle Assessment
EET	Emissions Embodied in Trade
ESA	European System of Accounts
EU-27	The 27 European Union Member States
EWEA	European Wind Energy Association
GDP	Gross Domestic Product
GTAP	Global Trade Analysis Project
GW	Giga Watt = 10^6 kW
GWh	Giga Watt hours = 10^6 kWh
GWP	Global warming potential
HAWT	Horizontal axis wind turbine
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IOA	Input-output analysis
kW	Kilo Watt
kWh	Kilo Watt hours
LCA	Life cycle assessment
MRIO	Multi-regional input-output
MW	Mega Watt = 10^3 kW
MWh	Mega Watt hours= 10^3 kWh
N_2O	Dinitrogen monoxide
NACE	Nomenclature des Activités Economiques dans la Communauté Européenne
NAICS	North American Industry Classification System

NAM	National account matrix
NAMEA	National accounting matrices with environmental accounts
nec	Not elsewhere classified
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NOK	Norwegian Kroner
NOx	Nitrous oxides
NVE	Norwegian Water Resources and Energy Directorate
OECD	The Organization for Economic Co-operation and Development
OWF	Offshore wind farm
OWP	Offshore wind power
OWT	Offshore wind turbine
pp	Percentage Points
ROW	Rest of the world
SIOT	Symmetric input-output tables
SNA	System of national accounts
SO_2	Sulfur dioxide
SOx	Sulfur oxides
SUT	Supply and use tables
TW	Terra Watt = 10^9 kW
TWh	Terra Watt hours = 10^9 kWh
UNC	United Nations Commodity Trade Statistics Database
UNI	United Nations Industrial Commodity Statistics

Chapter 1

Introduction

The European Commission projects a 20% increase in the total final energy demand for the EU-27 countries by 2030. The biggest growth will occur in the electricity sector, with a 38% increase by 2030. EU has limited potential for higher electricity imports from outside the EU; hence much of the increased demand must be covered by the EU countries. Due to this the total EU electricity generation is expected to rise by 35% by 2030 (European Commission 2008). If this additional electricity generation were to be covered by fossil fuels, this would result in a considerable growth in emissions of greenhouse gases. EU's future emission profile is strictly dependent on what will be the prevailing European energy policy. In order to avoid dramatic increases in emissions actions like improved power plant carbon intensity, improved energy efficiency and implementation of electricity from renewable energy sources must be undertaken.

One of the most prominent alternatives appearing in terms of renewable energy sources is wind energy, a renewable resource with a vast potential. The wind power sector has grown exponentially in the recent years. According to the European Wind Energy Association (EWEA) 65 GW of wind power were installed in the EU-27 at the end of 2008. This results in an annual production of 142 TWh, corresponding to 4.2 % of the total EU electricity demand (EWEA 2009). Onshore wind power is today accepted as an established industry. Offshore wind power (OWP), on the other hand, is an emerging industry which is currently facing a number of challenges. Among others, these are challenges in terms of technological performance, shortage of skilled personnel and appropriate auxiliary services, wind farm areas conflicting with other marine users, a fluctuating power output that leads to challenges in grid connection and energy system integration (EWEA 2009). On the other hand, offshore wind power represents an energy source with a huge potential. The wind conditions in the offshore environment is better than for onshore sites, and the large offshore area offers improved possibilities in building bigger farms and larger turbines. The power production per MW installed is about doubled for offshore wind power compared to onshore sites (Norwegian Energy Council 2007). Floating wind farms far off the coast could in the future improve land disturbance, and in this way mitigate the opposition from local communities (NVE 2008). A fully developed European offshore wind industry could deliver a capacity of several hundred GW. By installing wind power on less than 5 % of the North Sea surface area the electricity generated would cover roughly 25 % of the EU's electricity demand (EWEA 2007). The Scandinavian countries are interesting in the context of offshore wind power because they are countries with high potential for offshore wind energy. The wind power potential off the Norwegian coastline alone could in theory cover a substantial part of the EU's demand for renewable energy (Norwegian Energy Council 2007).

1.1 Background

The global society is starting to realize the damaging effect caused by combustion of fossil fuels, both in terms of environmental pollutions and in terms of its contribution to global warming. Nevertheless, the emissions of greenhouse gases are increasing continuously, and CO_2-emissions are expected to grow by 0.3% annually for the OECD countries and by as much as 2.2% annually for the non-OECD countries between 2000 and 2030 (Energy Information Administration 2009). The global society is in desperate need for solutions in order to reduce global emissions, and in this way moderate the disquieting projections of the consequence of global warming.

In March 2007 the European Council made an agreement with precise and legally binding targets for making the European economy a model for sustainable development, increasing the amount of renewable energy and reducing greenhouse gas emissions. One of the key targets set by the European Council involves a 20% share of renewable energy in EU energy consumption by 2020. In January 2008 this was followed up by a comprehensive proposal on energy and climate policy. One of the core elements in the new proposal is the sharing of burden between the member states, which states national targets for renewable shares[1] (European Commission 2008). The target for each country is set by a function of a percentage increase similar for all member states, and the country's economical situation expressed by its gross domestic product (GDP) per capita. For instance the UK must increase its renewable shares by as much as 13.7 percentage points (pp) by 2020, while the corresponding target for Romania is only 6.2 pp. The Scandinavian countries have potentially strict targets for

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[1] The calculations on renewable shares are based on final energy consumption by the end-user

increased renewable shares due to high GDP per capita. Denmark must increase its renewable shares 13 pp from the 2005 value of 17% to 30% by 2020. Due to a regulation stating that the renewable target for a country should not exceed 50% (Point Carbon 2008) Sweden must increase its renewable share from 39.8% to 49%, corresponding to a 9.2 percentage point increase. Norway is not yet incorporated into the renewable directive, and what will be the Norwegian target for increased renewable shares has not yet been decided. Due to the fact that 61.8% of the Norwegian energy consumption already is based on renewable energy sources, the 50% limit is already reached for Norway. Nevertheless, calculations performed by Point Carbon disregarding this limit state that the Norwegian renewable target potentially will be an increased renewable share of 14.5 pp up to a total of 76.3%.

In order to accomplish the European Union's ambitious goals on renewable energy a considerable European investment in new renewable energy sources is crucial. According to the burden sharing proposal each country needs to take its part of the responsibility for reaching the target of 20% renewable energy. Wind energy has a vital role to play as a massive, clean and affordable energy resource, and wind power investments could be an essential opportunity for countries in possession of rich wind potentials.

1.2 Previous work

Previous environmental studies related to offshore wind power consists mostly of LCA studies. These are both scientific reports and analysis performed by wind turbine manufactures. Since environmental analysis is a relatively novel field of study the availability of sufficient data is usually limited. Some manufacturers offer a more detailed set of data, however a complete set of data is usually hard to obtain. Nevertheless, numerous LCA studies of wind power exist, using various background data and assumptions.

In my previous project work (Tveten 2008) a life cycle assessment of a large-scale floating offshore wind farm (OWF) was performed. Parameters important to wind farm design, like capacity factor, life time, transmission distance and maintenance demand, were analyzed. The study stated an emission of 9.0 kg CO_2-equivalents per GWh of wind power produced. The sub-processes that were found to contribute most to the overall impacts were mainly the production of the wind power plants, responsible for almost 50% of the total costs, dominated by steel production for the wind turbine tower. Secondly, the production of the cable system was responsible for almost 20% of the total emissions, dominated by the large amount of copper. Thirdly, the emissions from operation and maintenance had a considerable contribution corresponding to more than 10% of the total emissions, dominated by fuel consumption and production of material for replacing broken parts.

The wind turbine supplier Vestas has performed an LCA study of onshore and offshore wind turbines employing specific data from Vestas and Vestas' suppliers. This study results in an emission of 5.23 kg CO_2-eq. per GWh of wind power produced (Vestas 2006). According to this study the environmental performance of onshore and offshore wind turbines are equal within the expected uncertainties. The higher material consumption for offshore wind turbines is hence compensated for by improved energy performance.

Other LCA studies of offshore wind power are Weinzettel, Reenaas et al. (2009) performing a study of the environmental impacts of a floating offshore wind farm located off the Norwegian coast, using process-based LCA. This study reports an emission of 11.5 kg CO_2-equivalents per GWh of wind power produced.
Schleisner (2000) performs a study of the Danish wind farm Tunø Knob using an LCA model developed by the Danish Risø National Laboratory. This study states an emission of 16.5 kg CO_2-eq. per GWh produced. Ardente, Beccali et al. (2008) use the traditional LCA approach in order to study an Italian offshore wind farm. This study states a more uncertain result with emissions between 8.8 and 18.5 g CO_2-eq. per kWh.

No study has been made using Input Output methodology for investigating the environmental and economical effects derived from the installation of offshore wind power. The studies mentioned above are based on the traditional LCA approach with limited system boundaries. The previous environmental studies of offshore wind power fail hence to include a complete system boundary. The effect on the total system by implementing the new technology into the economy is an important aspect when it comes to renewable energy. Since other industries are affected of the new technology in terms of changed electricity mix, a traditional LCA study fails to evaluate the complete picture. In this study it will be made an attempt to overcome some of these limitations.

1.3 Objectives and strategy

The primary objective of the study is to evaluate the life cycle environmental impacts of a future offshore wind power industry in Scandinavia. This study is a continuation of my previous work the fall 2008, where I performed a basic Life Cycle Assessment of offshore wind power generation (Tveten 2008). The strategy and method chosen in this study is defined in agreement with my supervisor, and it is chosen to extended the study from a basic LCA to an Environmental Extended Input-Output Life Cycle Analysis (EEIO-LCA)

In this study, a basic Multi-Regional Input-Output (MRIO) database will be developed. Further, the MRIO model will be extended to an EEIO-LCA by adapting specific data for the Scandinavian offshore wind power industry. Both the wind turbines, the required infrastructure for electricity transmission to the grid and other important parameters will be taken into account in the analysis. By studying the hybrid system the environmental performance and impacts caused by Scandinavian offshore wind power will be analyzed. This will be done both in terms of per-unit output and by means of scenario analysis. A baseline scenario and two scenarios for future offshore wind power development in Scandinavia will be generated. Scenarios of future industrial and environmental effect of offshore wind power will then be evaluated by using input-output based modeling. On the basis of these strategies for a sustainable offshore wind power industry in Scandinavia will be discussed.

1.4 Report structure

The next chapter covers the methodology that has been applied in the analysis. This includes an introduction to the approach of Environmentally-Extended Input Output Analysis, together with the extensions that are necessary in order to enable Environmental Input Output Life Cycle study. Chapter 3 contains a brief introduction to wind power technology in general, and the wind farm case study will be presented with its sub-systems and inventories. A cost study will thereafter be made. This will be followed by chapter 4, presenting the present situation for offshore wind power together with a short study of the European wind power potential. On basis of this, scenarios for future offshore wind installation will be developed. In chapter 5 the process of building the MRIO model is explained, including the process of hybridizing the system for offshore wind study. In chapter 6 the results of the analysis are presented with a brief discussion. The results will be discussed in a wider context in chapter 7, followed by a conclusion.

Chapter 2

Methodology

Two main frameworks have been used for this study, Life-Cycle Assessment (LCA) and, to a much higher extent, Environmentally-Extended Input-Output (EEIO) analysis. 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” (Robert H. Crawford 2007). A proper combination (hybridization) of both methods leads to a framework where each method’s weaknesses are covered up by each other's strengths. In this chapter, the emphasis has been put on input-output, which actually shares its main principles with LCA.

2.1 Introduction

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 is unanimously credited with the development of this powerful tool. 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). Very quickly, researchers have realized the interest of this framework when it is applied to environmental issues (Leontief 1970). Environmentally-extended IOA uses a stressor and a characterization matrix to connect economical flows to environmental impacts. 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 utilized 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 (NAICS, NACE,…), aggregation can generate a wide range of detail level, typically from 40x40 to 500x500 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 IOA is the A-matrix, which contains all the information about the industrial profile of any region, it is called the "inter-industry" or "technology" matrix, because it reflects the technology standards of an economy. This matrix has as many inputs as outputs, in a product-by-product matrix each term a_{ij} in this matrix giving how much money i is necessary to produce one monetary unit of product j; hence the A matrix is square. 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 1M€ of products from the metallurgical industry. When a final demand y is imposed on the system, we are then able to know the total industry or product output x necessary to meet this demand. The total production equals the internal production plus the demand itself:

$$x = Ax + y \tag{1}$$

From this we can derive an expression for the total output, x:

$$x = (I - A)^{-1}y \tag{2}$$

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:

$$Z = A\hat{X} = A\widehat{LY} = A(\widehat{I - A)}^{-1}y \tag{3}$$

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

$$A = Z\hat{X}^{-1} \tag{4}$$

2.2.2 Constructing symmetric A matrices

A challenge arises when it comes to construct a symmetric input-output table (SIOT), which is the core of IO analysis. The point is: one process is often associated with one product, but it is not the case in reality. In a SIOT, the total product output is distinct from industry output, q (product output) and g (industry output). Two matrices 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 immediately be derived from this basic set (^{t} denotes a transposing operation):

- The use coefficient matrix

$$B = U\hat{g}^{-1} \tag{5}$$

- The market share matrix

$$D = M^t\hat{q}^{-1} \tag{6}$$

- The product mix matrix

$$C = M\hat{g}^{-1} \tag{7}$$

Those three building bricks will now help to construct several SIOT. Indeed, two main assumptions can alternatively be considered, and two classification can be taken into account (product-by-product or industry-by-industry) leading to four possibilities to model a final symmetric table, which will be addressed in the next section.

2.2.3 Building symmetric A matrices

This section 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 utilized to fix data discrepancies, *e.g.* regarding the Czech input-output table which had to be reconstructed from supply and use tables. United Nations have created a very comprehensive manual to compile input-output tables, many more details can be found in their handbook of

IO tables compilation and analysis. (United Nations 1999) The equations presented hereafter are valid for a system with *m* products and *n* industries.

An industry-by-industry matrix using 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 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. Under this assumption, we must use the following equation:

$$A_{IT,nn} = DB \qquad (8)$$

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

A product-by-product matrix using industry technology assumption

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

$$A_{IT,mm} = BD \qquad (9)$$

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

An industry-by-industry matrix using product technology assumption

Now let's assume that each type of commodity produced is made with exactly the same technology, regardless of the industry which fabricates it. We are then considering the so-called “Commodity Technology assumption”. The expression hereafter will be used:

$$A_{CT,nn} = C^{-1}B \qquad (10)$$

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

A product-by-product matrix using 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:

$$A_{CT,mm} = BC^{-1} \qquad (11)$$

2.3 Multiregional input-output models

Production and consumption are naturally interlinked units in the economic system. Due to globalization 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 and 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 total economic output (x) in a region is calculated from the sum of intermediate (A) and net final demand (y), as described in equation (1). 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):

$$y = y^d + y^{ex} - m \qquad (12)$$

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 (United Nations 1999). Equation (12) then becomes,

$$x = (A^d + A^{im})x + y^d + y^{ex} + y^{im} - m \qquad (13)$$

and the imports import balance must be obtained,

$$m = A^{im}x + y^{imex} - m \qquad (14)$$

giving:

$$x = A^d x + y^d + y^{ex} \qquad (15)$$

which is the domestic activity of a given region. In order to include other activities than domestic, by 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 in and how much of this is triggered by a demand in other regions (Peters and 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 and Hertwich 2006):

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_5 \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2n} \\ A_{31} & A_{32} & A_{33} & \dots & A_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & A_{n3} & \dots & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_5 \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{n1} \end{pmatrix} \qquad (16)$$

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. Currently, there are good data on most OECD countries, but non-OECD country data are scare. Still, there are two major ongoing projects on developing MRIO datasets. The first one is the Global Trade, Assistance and Production project (GTAP) which has recently released version 7 of its MRIO model (Global Trade Analysis Project 2009). 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, Poliakov et al. 2009).

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 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 x s* matrix, were s_{kj} is the environmental burden *k* (e.g carbon dioxide emissions) per monetary output of sector *j*. The matrix e, telling the total environmental burden due to total monetary output, can then be written

$$e = sx = s(I - A)^{-1}Y \qquad (17)$$

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 characterization 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 relative contribution to a reference compound, so that the e vector gives total impacts in terms of emission equivalents of the reference compound. The vector of total impacts d is then calculated as follows:

$$d = Ce = CSx = C(I - A)^{-1}y \qquad (18)$$

Variations of this general equation can be used to provide useful information on a more detailed level. The most straightforward is perhaps the equation $E = \hat{s}x$, which breaks the emissions down sector-wise, such that Ei represents total direct emissions from sector i. An even more detailed representation of emission flows can be obtained from the equation $E = \hat{s}L\hat{y}$, where an element E_{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:

$$d_n = CSA^n \qquad (19)$$

and the cumulative impact after *n* tiers:

$$d_{n,acc} = CS\sum_{i=1}^{n} A^i y \qquad (20)$$

Note that $\lim_{n\to\infty} d_{n,acc} = CS(I - A)^{-1}y = d$. 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

(17) above, we can extract parts of A and Y to determine the EET from region r to region s:

$$EET_{rs} = S_r(I - A_{rr})^{-1}e_{rs} \qquad (21)$$

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 becomes:

$$EEC_r = s(I - A)^{-1}y_r^{EEC} \qquad (22)$$

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

2.5 Environmentally Extended Input-Output Life Cycle Assessment

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. These will be dealt with in the following section. Most of it is a summary of the article "Product Environmental Life-Cycle Assessment Using Input-Output Techniques" by Satish Joshi.

The sectors in the input-output model are often highly aggregated, so that 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 analyze 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 needs 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

$$\tilde{A} = \begin{bmatrix} a & a_{i,n+1} \\ 0 & a_{n+1} \end{bmatrix} \tag{23}$$

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

$$S = [s_1 \dots s_n \ \ s_{n+1}] \tag{24}$$

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

$$E = Sx = S(I - \tilde{A})^{-1}Y = SLY \tag{25}$$

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

$$Y = [0, \dots \dots 0, \ y_{n+1}] \tag{26}$$

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 x n+1] must be derived.

The first *n – 1* sectors of the new coefficient matrix is similar to the old coefficient matrix, A. 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.

$$A_{n,j} = \tilde{A}_{n,j} + \tilde{A}_{n+1,j} \qquad (27)$$

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 the new A:

$$A_{n,n} = (1-k)(\tilde{A}_{n,n} + \tilde{A}_{n+1,n}) + k(\tilde{A}_{n,n+1} + \tilde{A}_{n+1,n+1}) \qquad (28)$$

The share of the product of interest can be obtained from external sources. The technical coefficients for the product of interest, $\tilde{A}_{i,n+1}$, 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 $\tilde{A}_{n+1,j}$. 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, S_n, is then disaggregated the following way

$$S_n = (1-k)\tilde{S}_n + k\,\tilde{S}_{n+1} \qquad (29)$$

Chapter 3

Offshore wind power - Technological overview

3.1 Wind power technology

The energy from the wind has been used for several purposes throughout the history, from mechanical power to transportation purposes. Today there is an emerging interest in wind power for electricity production. The first commercial wind turbines were developed in the 1980 and after this the wind turbine technology has improved substantially. Several wind turbine designs have been developed; single- and multi-bladed concepts, up-, down- and cross-wind concepts, concepts with counter-rotating blades or with multiple rotors, etc. (Milborrow 2002). Today the most common wind turbine design is the three-bladed horizontal axis wind turbine (HAWT), which means that the axis of rotation is parallel to the ground. The wind power industry is currently moving towards larger wind turbines, and multi-megawatt turbines are already being produced. This trend is particularly prevailing for offshore wind turbines. Due to the increased foundation and transmission costs for OWP, the future OWFs will probably use turbines able to produce much greater power in order to counterbalance the capital investments (The Danish Wind Industry Association 2002).

In order to understand the process of turning wind energy into electric power many fields of knowledge are involved; meteorology, aerodynamics, electricity, structural, civil and mechanical engineering. In this section only some of the technological concepts are explained roughly in order to obtain a basic understanding of the system that constitutes a wind farm.

In modern wind turbines the *lift* force causes the wind turbine blades to rotate; the same aerodynamic force that acts on an airplane wing. The wind power is hence transformed into rotational mechanical power, causing the *drive train* rotate. The drive train consists of the rotating parts of the turbine; the *shafts*, the *gearbox*, *bearings*, *couplings*, a *brake system* and the rotating parts of the *generator* (Milborrow 2002). The gearbox is used to speed up the rate of rotation into a suitable rate for driving a standard generator. Finally, the generator transforms the mechanical power into electricity. The *yaw system* keeps the rotor shaft properly aligned with the wind. The yaw system includes a large *bearing* that connects the main frame to the tower. Figure 1 shows the main parts of a multi-megawatt turbine machinery.

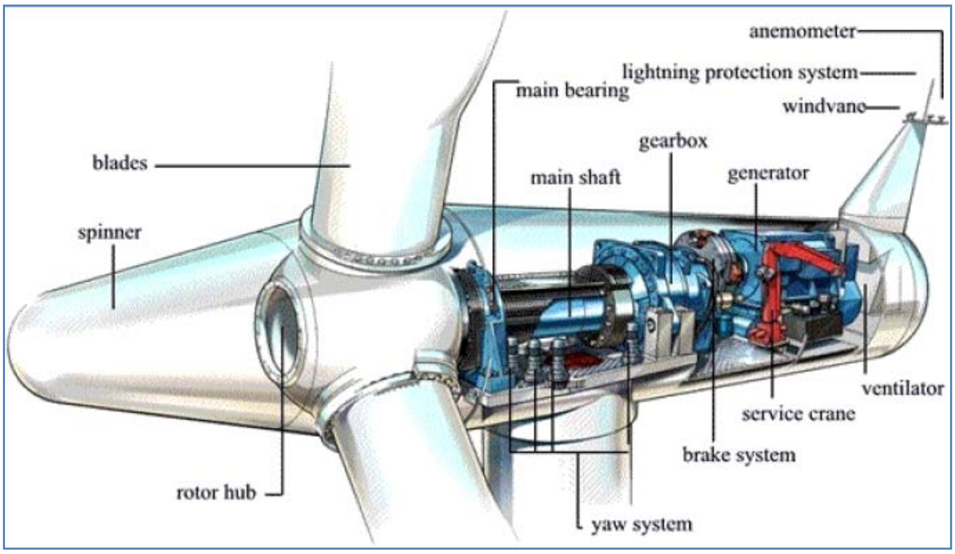

Figure 1: The parts of a Siemens 2.3 MW turbine machinery

Since the wind turbine produces power in response to the wind that is immediately available, the output is fluctuating. The system to which the wind turbine delivers power must therefore be able to handle this variability (Milborrow 2002). This could be done in different ways, from using specialized control systems to energy storage systems. Modern large capacity wind turbines are usually connected to large utility grids, and the electrical power from the wind turbine is transported via transmission lines. For OWFs this transport distance could be long, and a transmission system internally in the wind farm is often required. The key components and processes of an OWF are listed and explained roughly in Table 1.

Table 1: the main components of an OWF

	Wind farm components[2]
	**Rotor,** consisting of the hub and the blades of the wind turbine. The most common material used in the rotor blades are fiberglass reinforced plastic. For more detailed inventory, see Appendix C, Table 19 to Table 21
	Nacelle and other machinery, containing among other a generator, bearings, shaft, a brake system, a yaw system and usually a gearbox. Some wind turbines use specially designed low-speed generators and do not require any gearbox. The most common generator types are induction and synchronous generators, and synchronous generators are most common for wind turbines installed in grid connected applications. For inventory, see Appendix C, Table 19 to Table 21
	The **tower structure,** supports the rotor and the machinery. The most common tower design is the free standing type using steel tubes or other strong material like concrete. The tower height is typically 1 to 1.5 times the rotor diameter. Tower design is greatly influenced by the characteristics of the site. For inventory, see Appendix C, Table 19 to Table 21
	Foundation/ballast and mooring supports and stabilizes the wind turbines. There are several foundation designs available today, and the design chosen for one specific wind farm will vary according to parameters like water depth and seabed conditions. For inventory, see Appendix C, Table 19
	**Offshore inter-turbine cables**, which are typically three-phase 30-36 kV cables, connect the turbines in collection circuits and feeds the substation. Each collection circuit is usually rated to 30 MW. For inventory, see Table 22, Appendix C.
	High Voltage Transmission cables are typically between 100 and 220 kV and transmit the power from the wind farm to shore. The transmission could be done by HVAC or HVDC. A HVDC transmission requires HVAC/HVDC converter stations both offshore and onshore. For inventory, see Table 22, Appendix C.
	**Offshore substation** steps up the voltage for the transmission to shore and/or converts the electricity from HVAC to HVDC. High voltage is needed for long distance transmission in order to reduce electrical losses. Most future OWFs will be large and/or located far from shore, and will hence require one or more offshore substations. For substation inventory, see Table 23, Appendix C.
	The onshore substation adapts the voltage level to the grid level[3].

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[2] Pictures are obtained from the following sources:

Wind turbine:	www.popsci.com
Cables:	http://www.abb.no/
Offshore substation:	http://w1.siemens.com/entry/cc/en/

[3] The possible need for upgrading of the national grids has not been specifically studied in this analysis.

3.2 Defining the case study

An attempt was made at modeling a typical “average” future Scandinavian OWF. The wind farm life time was assumed to be 25 years. Normal life time ratings for land based wind systems are 20 years, but offshore wind conditions are more uniform, resulting in less wear and extended life time as a consequence (International Starch Institute 2005). A constant capacity factor of 37.5% was assumed, corresponding to 3 300 annual hours of full load. This number covers future increase and decrease in production due to variables like newer and larger turbines, lower wind regimes and transmission losses (EWEA 2009). The data for the wind farm dimension is inspired by a Norwegian wind farm planned by the Norwegian energy company Lyse near Karmøy in Norway (Lyse 2007). This is a wind farm with 60 turbines, each with the capacity of 5 MW, giving a total capacity of 300 MW. For this wind farm dimension the need for two offshore or onshore transformer substations is assumed. An average distance from shore for a Scandinavian wind farm is hard to predict, since the acceptance of wind farms near the coast will differ between the Scandinavian countries. For Norwegian OWFs NVE states that OWFs should be situated more than 20 km off shore. In order to minimize the costs of the infrastructure the wind farms should however be situated as close to shore as possible (NVE 2008). In order to take both these restrictions into account, the distance to shore for an average future OWF was estimated to 30 km.

3.3 Cost study

In order to integrate the foreground system into the MRIO model the whole cost profile of a wind farm was taken into account. The cost per MW installed OWP is around 50% higher than for land based wind power (EWEA 2009). The structures need to resist rough weather conditions, and there is stricter logistics associated with operating in a maritime environment than on land. Installation, construction and grid connection is also significantly more expensive for offshore applications. These costs depend on parameters like distance to shore and water depth. For instance the offshore transmission costs will increase with increasing distance to shore, and the foundation, mooring and installation costs will increase with increasing ocean depths. Operation expenditures are significantly more expensive for offshore installations than for onshore sites. This is partially due to the fact that access to the wind farm site depends on the access to a vessel and/or a crane, and the need for good weather conditions (G.J.W. van Bussel 1997).

As proposed above, each future wind farm will be different and the cost will depend on many parameters like distance to shore, water depth, turbine size, wind farm size and so on. Therefore, average OWF statistics has been used in order to obtain a realistic case study. The breakdown of the investment cost and operation and maintenance cost is assumed to follow the same trend as OWFs installed today. This cost breakdown is estimated according to data from the Danish OWFs in Horns Rev and Nysted (EWEA 2009). The costs of OWP are expected to fall as the industry gains more experience in this sector and due to larger turbines that will capture higher wind speeds. Nevertheless, for simplification in this study it is assumed that the installation and operation costs will remain constant in the time frame from 2000 to 2030.

In order to compile a foreground system for a future Scandinavian wind farm, a cost breakdown of the wind farm life stages and components was performed. The main components of a wind farm has been included, as well as key processes like operation and maintenance and other important processes included in the wind farm cost structure. Figure 2 shows the life-time cost breakdown of the wind farm components.

Operation and maintenance costs
The operation and maintenance (O&M) cost was estimated to 16 €/MWh of wind electricity generated. According to this estimate, O&M cost of the wind farm amounts to around 38% of the total life time costs. 26% of the O&M costs is connected to wind farm maintenance and repairs, and the rest of the cost includes the following (EWEA 2009):

- Administration costs (21%)
- Land rent (18%)
- Insurance costs (13%)
- Power from the grid (5%)
- Miscellaneous (17%)

Investment costs
The average expected investment cost for a new OWF is currently in the range of 2.0 to 2.2 million €/MW (EWEA 2009). The 2006 average investment cost of 2.1 million €/MW, was chosen as an estimate in this study. A 300 MW wind farm with a capacity factor of 37.5% and life time 25 years results in a life time electricity generation of 24.6 TWh. Investment costs are thereafter found by dividing the total wind farm investment cost by the total life time electricity production:

$$\frac{2.1\frac{M€}{MW}\cdot 300MW}{300MW\cdot 37.5\%\cdot 8760\frac{h}{year}\cdot 25years} = 25.6\ €/MWh$$

Cost breakdown

The breakdown of the costs over wind farm components and processes was provided partly from EWEA and partly from Offshore Design Engineering (ODE). This shows that the wind turbine costs amount to almost 50% of the total investment costs, the transmissions system more than 20% and the foundations about 16%. Other investment costs are installation and dismantling of the wind farm, and management costs like wind farm design and analyses. Installation and dismantling costs amount to around 4.8 % of the total life time costs. This sub-category includes assembling, installation and dismantling of the following components

- the foundation or the ballast and anchoring
- the wind turbines
- the onshore and/or offshore substation(s)
- the cables and the transmission system

The total resulting cost distribution is shown in Figure 2, where the percentages show in which degree the different components contribute to the total cost (Offshore Design Engineering 2007; EWEA 2009).

The cost of raw materials also has a high influence on the cost trend of OWFs. The price of steel plays an important role in particular since the turbines consist essentially of steel (Offshore Design Engineering 2007). In order to obtain a more accurate result it was also chosen to include the most important materials used in a wind farm installation. The materials that were chosen to include in the foreground system were the metals copper, lead, steel and aluminium, since these materials are used in a considerable scale in the wind farm components (ABB; Princeton Energy Resources International 2001; Multibrid 2008). Additionally, due to the large amount used in the blades, glass reinforced plastic was also chosen to be studied in the foreground system. The materials and their application are listed in Table 2. For more detailed information about the inventory of each sub component studied in the foreground system see Table 19 to Table 23 in Appendix C.

Table 2: Materials included in the foreground system

Material	Wind farm use
Copper is applied in the electric circuits and transformers. Copper is used in both the wind farm nacelle, in the substation and in the cables.	Nacelle - 27.3 tons/turbine Substations - 13.5 tons/substation Cables - around 33% of total mass
Aluminium has many other areas of application and is used both in electric circuits and cables, in the wind turbine, as well as in the substations.	Nacelle - 7.3 tons/turbine Substations - 0.4 tons/substatioin Cables - around 4% of total mass
Lead is used to a limited extent in the substations and is one of the key elements in the sea cables.	Substations- 1.7 tons/substation Cables - around 27% of total mass
Glass reinforced plastic It's a versatile material that combines light weight with strength and is used as main element in the turbine blades	Rotor blades - 16 tons/blade Nacelle - 2 tons/turbine
Steel is widely used in all wind farm components, especially in the tower, which consists almost exclusively of steel	Wind turbine - 520 tons/turbine Cables - around 30% of total mass Substations - 210 tons/substation

In order to convert between monetary and physical units in the hybrid MRIO model an average per-unit costs of each material was estimated (Morici 2005; UNC 2009; UNI 2009).

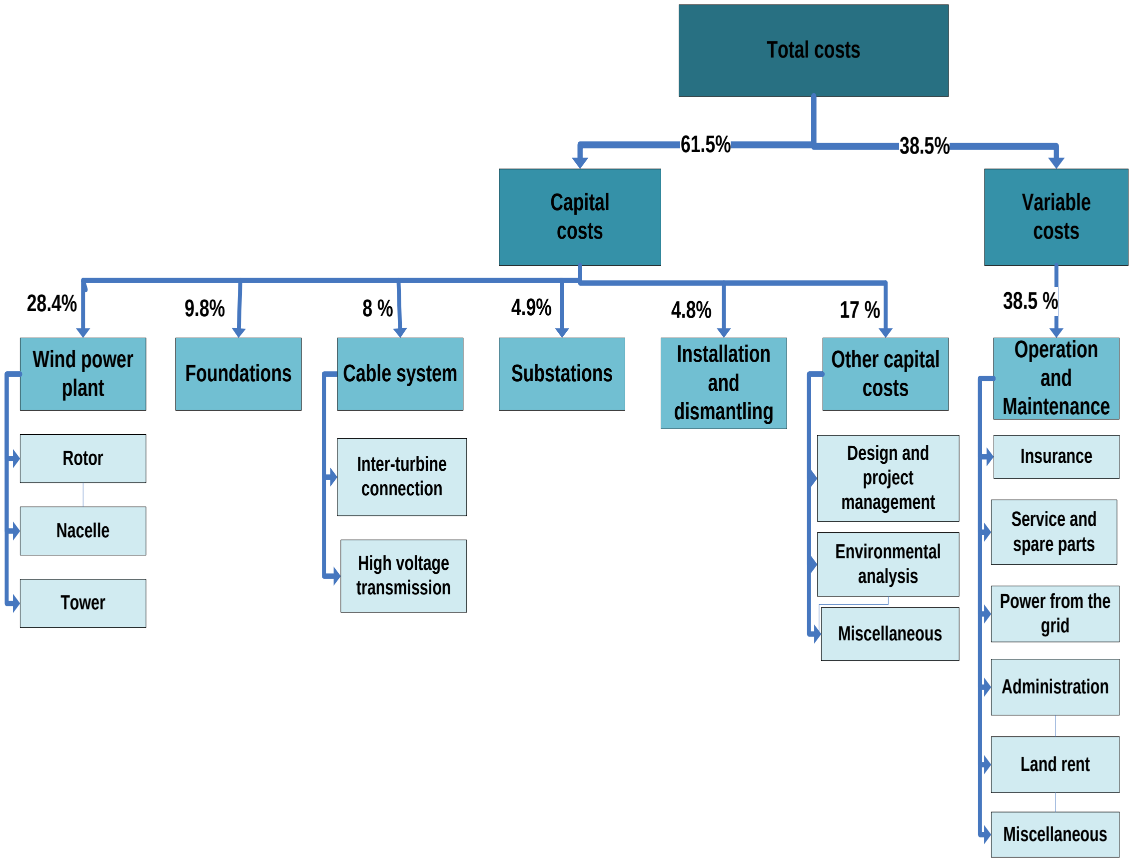

Figure 2: Breakdown of the life time cost of an average Scandinavian wind farm

Chapter 4

Present and future situation of offshore wind power

4.1 Offshore wind power – Current status

By January 2009 there were 33 operating offshore wind projects in the world, resulting in a total capacity of around 1 470 MW. Many of these wind farms are large-scale and fully commercial. There are currently eight countries with operating OWFs, and each of these countries' share of the total installed capacity is shown in Figure 3 (EWEA 2009). The map of Figure 4 shows the localization of all the installed offshore wind projects January 2009, including large commercial wind farms, smaller demonstration projects and single offshore wind turbines.

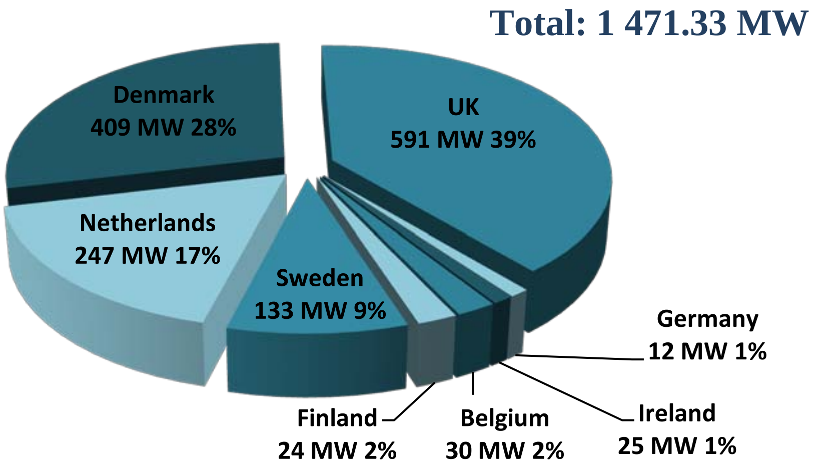

Figure 3: The capacity and localization of the operating OWFs (Jan. 2009)

All existing commercial wind farms are located on shallow water with foundations fixed to the sea bed. The choice of foundation type for an OWF depends on many different parameters, like sea depth, soil and sea bed conditions, environmental impacts, construction methodology, turbine size, turbine weight and foundation cost. Large bottom fixed wind farms are currently being built in countries like the UK, Denmark, Sweden and Germany.

Figure 4: The existing OWF projects, January 2009

There is currently research and development activity in the field of floating wind power technology. The wind conditions improve when moving further from shore, giving a great incentive for moving wind farm installations towards deeper water (NVE 2008). Additionally, floating wind turbines represents a more suitable technology for countries like Norway, where the community raises severe demands for the localization of wind turbines in terms of visibility from shore. However, there are many challenges connected to building a wind farm far away from shore. Moving further away from shore demands greater amounts of expensive sub-sea cables, and longer transmission distances results in higher investment costs and higher energy losses. Floating wind turbines have strict requirements for properties like robustness and stability, and the technology for floating offshore wind turbines is still immature. The first model of a floating wind turbine, developed by Hywind, was set afloat June 2009 (StatoilHydro

2008). The turbine will work as a demonstration model for the future floating wind turbines, and it is predicted that commercial floating wind power plants will not be installed until 2015-2020.

4.2 Offshore wind power potential

In a study undertaken by the European Environment Agency this year the European wind energy resources were analyzed. The maximum technical potential were estimated based on wind speed data together with projections on development in the wind turbine technology (EEA 2009). By integrating social and environmental factors into the analysis the constrained potential and the economically competitive potential for wind energy development were found. For OWP the constrained potential takes into account local opposition of placing wind farms visible from shore, as well as possible conflicts with shipping, tourism and the petroleum industry. The economical potential takes the forecasted future investment and operation costs of OWFs into account, relative to projected average energy generation costs based on parameters like future CO_2- and oil prices.

The EEA report states considerable European offshore wind energy potential. The technical potential is vast; amounting to as much as 30 000 TWh by 2030, corresponding to seven times the projected European energy demand in 2030[4]. However, this is not a very realistic number. The projections for the constrained and economical competitive potentials, taking political and economical constraints into account, are more realistic estimates for the offshore wind potential. By 2030 the constrained and economical potentials are estimated to 3 500 and 3 400 TWh annual production, respectively. This corresponds to around 80% of the total European energy demand. This states that the wind energy resources in Europe are considerable, and could play a major role in order to accomplish the European renewable energy targets.

Figure 5 shows the mapping of hours of operation with maximum power for OWP in Europe[5] (Garrad Hassan). This map shows that some of the largest offshore wind potentials can be found in areas in the North Sea, the Baltic Seas and the Atlantic Ocean. The Scandinavian countries hold a considerable share of the offshore wind potentials. According to the EEA study the unrestricted technical potential for Denmark, Norway and Sweden amount to around 2750, 1900 and 1500 TWh in 2030, respectively. This corresponds to more than 20% of the total European technical potential.

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[4] European Commission projections for energy demand based on a “business as usual” scenario.

[5] 4500 hours of operation corresponds to a capacity factor of 51. 4%. The average assumed capacity factor for a future offshore wind farm, estimated by EWEA is 37.5%, corresponding to 3 300 hours of full load annually.

According to the Norwegian Energy Council the Norwegian offshore wind potential is almost unlimited. Only factors like technological constraints and limited transmission grid set limitations for the Norwegian potential. The council states that 200 TWh of OWP could be installed near the coastline based on established technology. Further away from shore, until a 60 meters depth is reached, bottom fixed technology could give an additional potential of 800 TWh. Finally, by moving to greater depths and implementing floating technology, the potential increases dramatically (Norwegian Energy Council 2007).

Table 3: OWP potential study (European Environment Agency (EEA) 2009).

	2020		**2030**	
	Potential [TWh]	**Share of demand**	**Potential [TWh]**	**Share of demand**
Projected energy demand	4 078	-	4 408	-
Technical potential	25 000	6-7	30 000	7
Constrained potential	2 800	0.7-0.8	3 500	0.8
Economical competitive potential	2 600	0.6-0.7	3 400	0.8

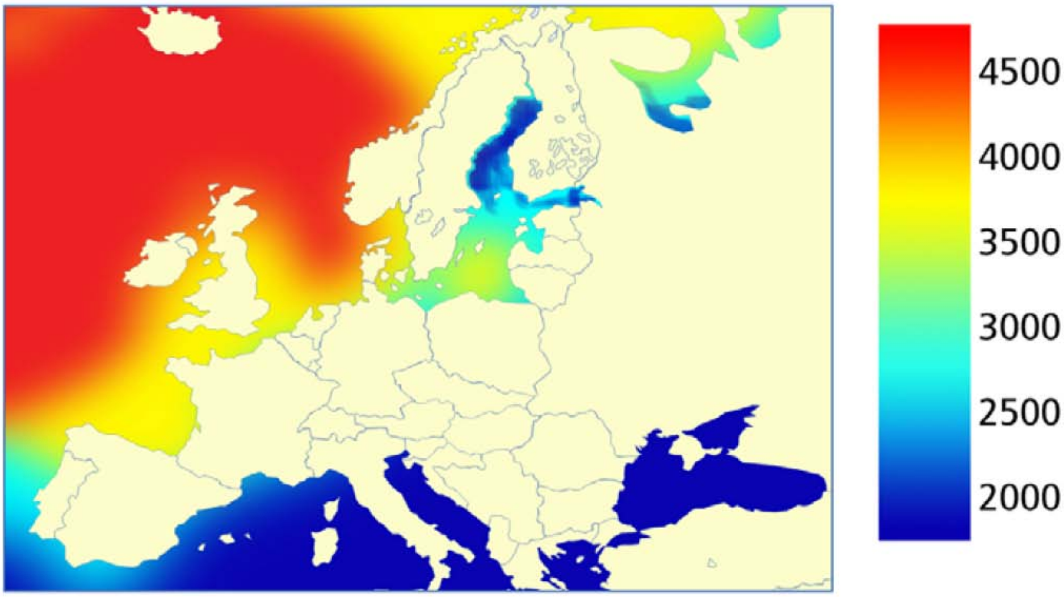

Figure 5: Hours of operation with maximum power for OWP in Europe

4.3 Scenario modeling

In this study scenarios from 2000 to 2030 have been developed. The baseline scenario was modeled according to results provided by the EU report “Energy and Transport – Trends to 2030”. The data of the EU report is derived from the PRIMES model, a partial equilibrium model for the EU energy system. The PRIMES model uses EUROSTAT as main data source to simulate trends and policies for EU and each of its member states. For the EU member states the 2007 update of the “Energy and Transport – Trends to 2030” has been used, while data for Norway is derived from the 2003 report, since this was excluded from the 2007 report.

4.3.1 Baseline scenario

The main procedure for modeling a baseline scenario on the basis of the MRIO model was to scale the system according to future changes in GDP. The GDP scaling was made for the final demand matrix Y. If for instance a country’s GDP was projected to increase by 10% from 2000 to 2010 the country’s final demand in 2010 was set to the 2000 value multiplied by a factor of 1.1. This was done both for the demand of domestic commodities and for the demand of imported goods. An important assumption for this approach is that there is cointegration between future GDP and consumption. This implies that there is a statistically significant connection between the future consumption and the GDP expansion for a country.

The PRIMES model deal with numerous projections, including projections on future energy demand. Figure 6 gives the graphical expansions of the GDP indexes and the index of the Energy consumption for the Scandinavian countries, Poland and rest of Europe (European Commission 2008). Poland is included to show that the GDP- and energy indexes vary highly for different European countries. The graphical expansion gives a picture of the accuracy of scaling the future energy demand according to GDP projections. Since the main focus in this study was to examine implementation of OWP into the electricity sectors it was considered more accurate scaling the electricity sectors using projections on energy demand instead of GDP projections. The electricity sectors for all regions were hence scaled according to projections on energy demand, while all other sectors were scaled according to GDP.

In the baseline scenario the technology mix for the industry sectors was assumed to be unchanged, hence no adjustments were made to the technology matrix A.

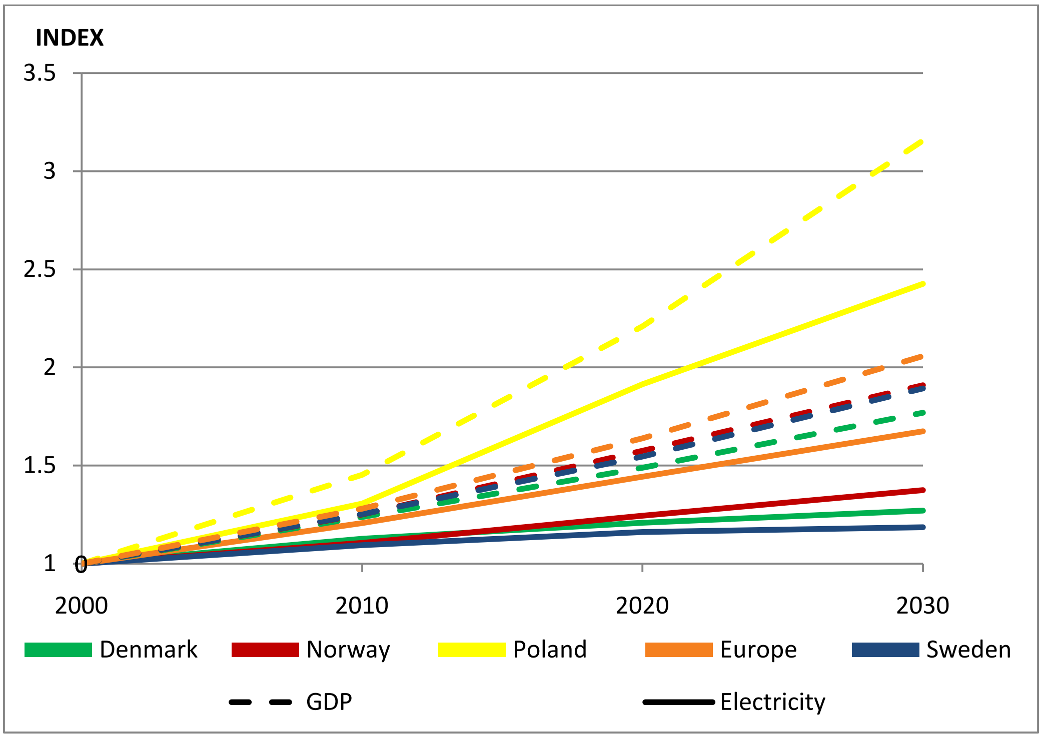

Figure 6: GDP indexes for, together with projections on energy consumption.

4.3.2 Scenarios of offshore wind power production

The baseline scenario was defined as a “Low” scenario, assuming no further OWP installation in the Scandinavian countries. The Medium scenario is defined as the most likely outcome. The High scenario is defined as the highest “credible” outcome of the future Scandinavian offshore wind installation. The following assumptions and data were used in order to develop scenarios for future Scandinavian offshore wind installation:

Denmark

The projections for the development in the Danish OWP industry were provided by “Energistyrelsen”, a board under the Danish Ministry of Climate and Energy. It is assumed that the development ramps linearly from the 2009 level towards the 2025 target. The Danish High scenario is a +10% deviation from this trend (EWEA 2008). The share of OWP was not given specifically, but the total wind power installation and the share of OWP was given both for current situation and for the target year 2025, and rest of the data were extrapolated from this. The offshore wind installations are assumed to be distributed equally over the western (Dk1) and Eastern Denmark (Dk2). For a more detailed explanation, see Figure 7.

Norway

The Norwegian estimation of wind power installation is provided partly from the NVE and partly from the research organization SINTEF. The Norwegian projections are based on actual wind farms that have applied for – or received building approval. These projections assume that the first Norwegian offshore wind installation will be built by 2015, and be located off the coast of Central Norway (No2). Wind installations will be built in Southern Norway (No1) by 2020, and in Northern Norway (No3) by 2030 (EWEA 2008).

Sweden

The Swedish projections are provided by numerous sources, among others Elforsk, the Swedish Energy Agency, Nordel, Vattenfall and Swedish Wind Power Association (SVIF). For 2010 the data is based on actual ongoing projects, where the High scenario assumes that all these projects will be fulfilled, and the Medium scenario assumes that only a share of this will be realized until 2010. The 2020 estimation is provided by SVIF, which assumes a cumulative capacity of 4550 MW offshore by 2020. The Medium scenario assumes this goal is nearly obtained by 2020, while the High scenario assumes the goal is surpassed. The Medium 2030 scenario is a more rough estimation that 10% of the gross demand will be covered by wind power. The Swedish projections are divided between South (Se1), Middle (Se2) and North (Se3). The scenarios for all three countries are given in Table 4.

Table 4: Cumulative MW of installed capacity (EWEA 2008).

Unit: [MW]		**2 010**		**2020**		**2 030**	
		M	**H**	**M**	**H**	**M**	**H**
Denmark	Dk1	371	433	911	1 003	1 757	1 933
	Dk2	371	433	911	1 003	1 757	1 933
	Total, DK	743	865	1 823	2 005	3 515	3 866
Norway	No1	0	0	90	320	450	1 290
	No2	0	0	390	1 570	1 400	4 280
	No3	0	0	0	0	650	1 730
	Total, NO	0	0	480	1 890	2 500	7 300
Sweden	Se1	400	550	2 000	2 500	2 800	5 000
	Se2	0	0	500	1 000	1 000	2 000
	Se3	0	0	1 300	2 000	2 000	4 000
	Total, NO	400	550	3 800	5 500	5 800	11 000
Total		**1 143**	**1 415**	**6 103**	**9 395**	**11 815**	**22 166**

4.3.3 Scenarios for power export

The power grid for 2005 was provided by Statnet, giving the existing cables and subsea cables, including NorNed, a planned subsea cable connecting the Norwegian and the Dutch distribution grid. NorNed was installed in 2007 and was commercially operative in 2008, with a transmission capacity of 700 MW; hence this connection is included in this study. In a model of a future Norwegian offshore transmission grid by 2020-2025 developed by Statnett, it is also assumed that connections will be built from Norway to both Germany and the UK (Statnett 2008). It is therefore assumed in this study that subsea connections between Norway and Germany and between Norway and the UK have been built. Both of these connections was modeled to have the same capacity as the NorNed connection; a 700 MW transmission capacity.

The power export for the Scandinavian countries was modeled according to the distribution grid both internally in the Nordic countries and the connection between the Scandinavian countries and rest of Europe. The export shares for the three countries were assumed to be in accordance with the distribution of the transmission capacity, so that the share of export from the Scandinavian country $C^{Exp}$to an importing country C^{Imp} is equal to the share that the transmission capacity from C^{Exp} to C^{Imp} make of the total transmission capacity from C^{Exp} to all countries.

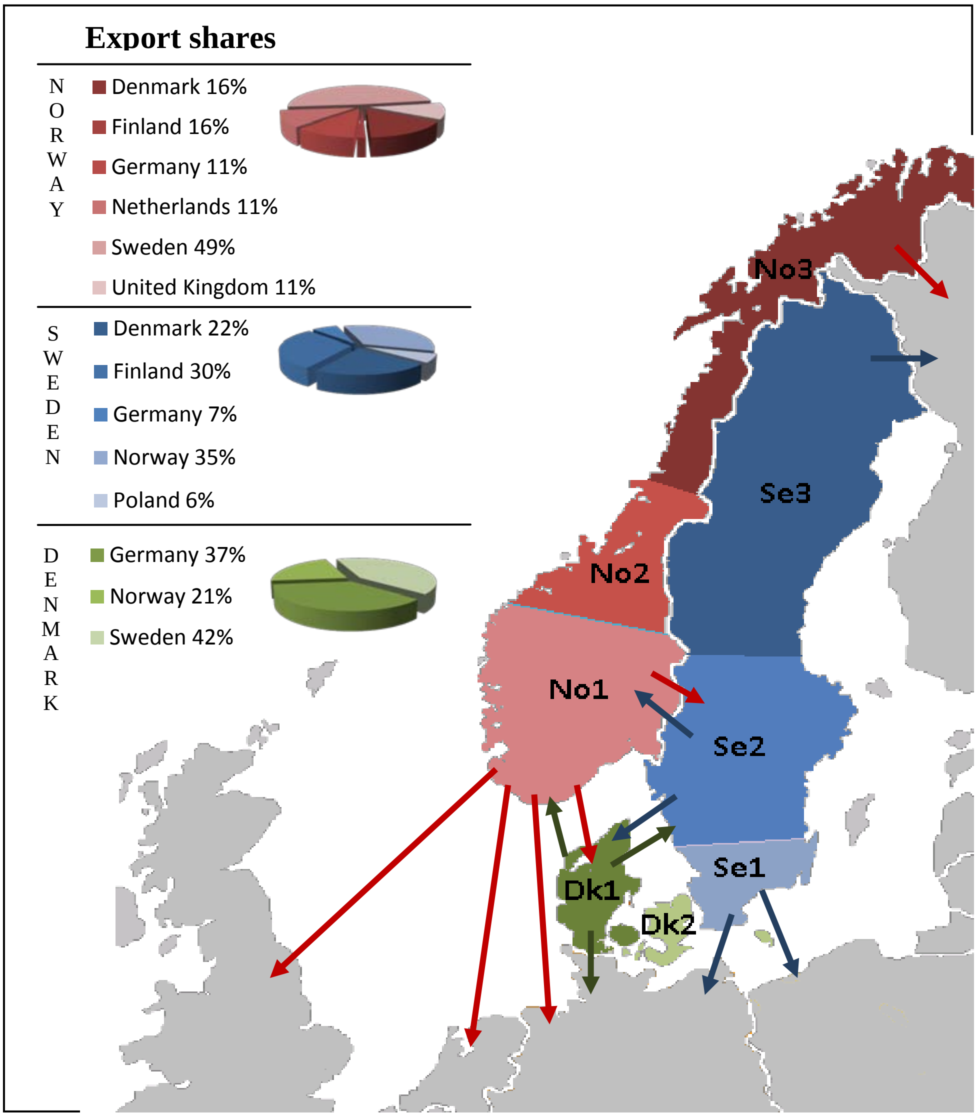

Figure 7: The Scandinavian countries and the export patterns assumed in the scenarios

Chapter 5

Building a Multi-Regional Input-Output Model

5.1 Introduction

In order to be able to use the input-output methodology described previously, a complete set of input-output tables must be constructed. These include the main Z matrix containing domestic inter-industrial flows for all the regions modeled, as well as corresponding matrices describing trades between all region-sectors to every other region-sector – and it includes matrices of final demand, value added and emissions for all region-sectors. Based on the framework of the EXIOPOL project (Tukker, Poliakov et al. 2009), such a system was constructed using data from ESA supplied with other data sources. The system focuses on Europe, but the rest of the world is included as larger aggregated regions to ensure completeness of global trade flows.

5.2 Compiling the inter-industry flow (Z) and final demand (Y) matrices

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

5.2.1 Data collection

The challenge in modeling 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 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 was gathered from. A later section will show how each source can be connected to each other, since discrepancies are unavoidable, in terms of currency, sector disaggregation or year of collection.

The main information, i.e. the flows themselves, was obtained from Eurostat. The reference year is 2000. The nature of the data is relatively the same for all of European countries: tables of 59 NACE[6] 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 0. 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 build a Z-matrix with more than 2 regions. A challenge was therefore to determine the import shares from industry to industry and from country to country. The GTAP data was used for this purpose, as it employs an 87 region world trade model. Throughout the compilation of those matrices into a bigger one, currency conversion had to be performed, relying on Euro rates adapted from http://www.oanda.com. From Eurostat (2009), 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.

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[6] Nomenclature des Activités économiques dans la Communauté Européenne

5.2.2 Approach

Computing $\boldsymbol{Z_{ii}^{d}}$

The first and simpler operation is the construction of the diagonal area of the Z-matrix. There is indeed only one operation that has to be processed, which is currency conversion, since the monetary unit (M€) must 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 $\boldsymbol{Z_{ij\neq j}^{m}}$

The method used to obtain the disaggregated $\boldsymbol{Z_{ij\neq j}^{m}}$ (import) matrices was a breakdown of the import flows from Eurostat database's import matrix Z^{m}or each country. Pretty accurate information can be found in the GTAP data about each country's import shares. Unfortunately the sector disaggregation (57 x 57) used in this database is different from the NACE-based classification that was to be used in the final output matrix (59 x 59). A bridging operation from 57 x 57 to 59 x 59 had to be processed to get the right import shares that could be utilized 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 $b_{GTAP\rightarrow ESA}^{c}$, where c can be any of the considered countries) consists of a void matrix (output dimension x input dimension, or vice versa) which is filled with ones where two sectors match. Furthermore, in the present case, row disaggregation must be processed when a GTAP sector had to be distributed into more than one ESA sector. Shares were obtained from the y^{e} (export demand) in the ESA data.

Formally,

$$b_{ij}^{c} = \frac{b_{ij,unit}^{c} y_{i}^{e}}{\sum_{1\leq i\leq 59} b_{ij,unit} y_{i}^{e}} \qquad (30)$$

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

Where b_{ij}^{c} is the element at row *i* and column *j* from the bridge matrix for country *c*. Besides, $b_{ij,unit}$ stands for the bridge matrix with only zeros and ones, being rather a “correspondence matrix”.

As far as the shares are concerned,

$$shares_{GTAP,ij} = \frac{\check{Z}_{GTAP,kl}}{\sum_{1\leq j\leq 87} \check{Z}_{GTAP,kl}} \qquad (31)$$

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

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

Consequently,

$$shares_{esa} = b^{c}_{GTAP \to ESA} shares_{GTAP} \qquad (32)$$

A last bridge had to be made in order to match ESA country distribution, from the GTAP 87 country-framework. After that, the shares could finally be applied to every $Z^{m}_{ij \neq j}$, all of them completing the Z matrix. Note that currency conversion was also applied at that stage.

5.2.3 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" (ROW) layer was added through the attachment of 8 regions' trade and emissions flows. A total of 31 regions covering the whole global trade were thus 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 was gathered from GTAP. This part of the compilation was 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 reported amount of emissions from electricity production is likely to vary a lot from source to source. To increase the model's level of detail the electricity sector was broken down into six different sectors according to energy source. Information about electricity source mixes can be found in Appendix A, Table 14, as retrieved from (International Energy Agency).The electricity sectors are:

1. Hard coal,
2. Hydropower,
3. Nuclear,
4. Wind,
5. Natural gas,
6. Petroleum and NEC.

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

Row disaggregation

This part of the work is pretty straightforward; it consists of building bridges for all the countries, from a correspondence matrix (with only ones and zeros) 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 was that a simple bridge could not be directly applied. As explained before, inputs must be treated independently, column-wise. Table 5 presents the way inputs were broken down.

Each “x”' was substituted by the energy mix share of each source, relatively to the other sources which show an “x” 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 was 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 1 a distribution over all electricity sources has been made, according to energy shares. At this stage, European countries had 64x 64 sectors matrices and rest of the world countries were represented by 62 x 62 matrices.

Table 5: The allocation of the economic flows towards electricity sectors (Hawkins 2009).

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

The Z_{bb} matrix is ready, and can be represented as in Figure 8.

$$
\begin{array}{c|c}
\overbrace{\hphantom{Z^m_{AT\to AT}\quad Z^m_{AT\to BE}\quad Z^m_{AT\to CZ}\quad \cdots\quad Z^m_{AT\to UK}}}^{\text{EU23, 64 sectors}} & \overbrace{\hphantom{Z_{AT\to Oc}\quad \cdots\quad Z_{AT\to Af}}}^{\text{RoW, 62 sectors}} \\
\left(\begin{array}{ccccc}
Z^d_{AT} & Z^m_{AT\to BE} & Z^m_{AT\to CZ} & \cdots & Z^m_{AT\to UK} \\
Z^m_{BE\to AT} & Z^d_{BE} & Z^m_{BE\to CZ} & \cdots & \vdots \\
Z^m_{CZ\to AT} & Z^m_{CZ\to BE} & \ddots & & \vdots \\
\vdots & & & \ddots & \vdots \\
Z^m_{UK\to AT} & \cdots & \cdots & \cdots & Z^d_{UK} \\
\hline
Z^m_{Oc\to AT} & \cdots & \cdots & \cdots & Z^m_{Oc\to UK} \\
\vdots & & & & \vdots \\
Z^m_{Af\to AT} & \cdots & \cdots & \cdots & Z^m_{Af\to UK}
\end{array}\right.
&
\left.\begin{array}{ccc}
Z_{AT\to Oc} & \cdots & Z_{AT\to Af} \\
Z_{BE\to Oc} & \cdots & Z_{BE\to Af} \\
\vdots & & \vdots \\
\vdots & & \vdots \\
Z^m_{UK\to Oc} & \cdots & Z^m_{UK\to Af} \\
\hline
Z^d_{Oc} & \cdots & Z^m_{Oc\to Af} \\
\vdots & \ddots & \vdots \\
Z^m_{Af\to Oc} & \cdots & Z^d_{Af}
\end{array}\right)
\end{array}
$$

Figure 8: Disposition of national matrices in the MRIO Z-matrix.

5.2.4 The A matrix

The scenario modeling 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:

$$A = \tilde{Z}\tilde{g}^{-1} \tag{33}$$

5.2.5 Assumptions

Along the compilation, a non-negligible number of assumptions have been made, depicted hereafter.

Modeling 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 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

One should also notice 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 inevitably have to be considered when it comes to disaggregating the electricity sector. First of all, the physical flow shares were used to split the row “Electricity production”. This means that the electricity price was assumed constant regardless of what the means of production were. Secondly, the same energy mix was used when two electricity production sectors (or more) had 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 currency/€ ratio over year 2000, there is no way to take the rate fluctuations into account, as the Z matrices give total flows along the year.

5.3 Compilation of the S-matrix

A stressor matrix providing industry specific environmental data for all European countries in the multi-regional input-output table were made using the NAMEA[7] framework. 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 (Organisation for Economic Co-operation and Development 2005). This makes it a suitable tool for environmental Input-output analysis. Data from the NAMEA framework was 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[8], 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

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[7] National accounting matrices with environmental accounts

[8] Non-methane volatile organic compounds

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 emission tables had to be adjusted to fit. 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 statistical agency (ESA) database.

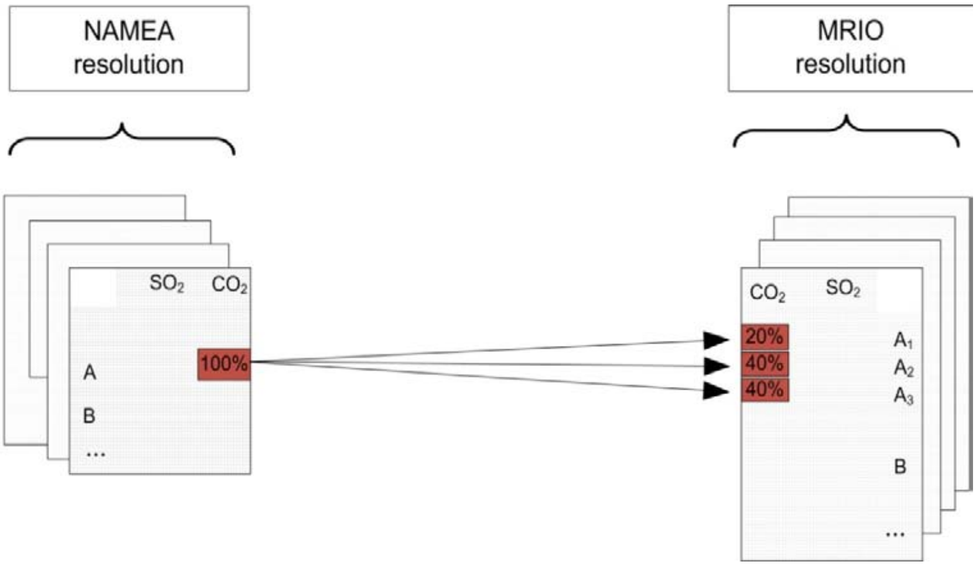

Figure 9: Graphical representation of the disaggregation of sectors.

For some countries, the NAMEA stressor data were incomplete, and several assumptions had to be made in order to compile the stressors 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 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.

Table 6: Proxy countries used for the S matrix modeling

Country estimated	Missing data	Substitute country
Austria	All SOx 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
Luxemburg	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

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 the Ecoinvent database (Frischknecht and Jungbluth 2007). The physical data from the database were translated 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.

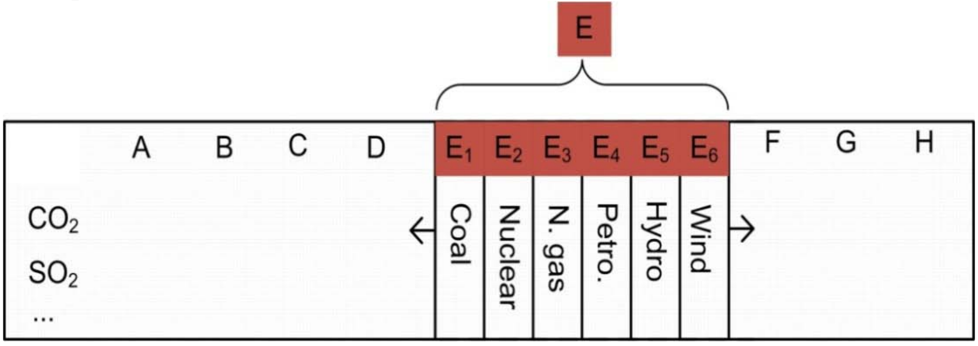

Figure 10: Graphic representation of disaggregation using the total output shares.

5.4 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 is also the source of the data in 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 whole sectors. 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.

5.5 Adjusting system for offshore wind analysis

As described in Chapter 2 the environmentally extended MRIO model has a complete and broad system boundary in contrast to an LCA model. However, adjustments need to be made for enabling a more specific study of offshore wind electricity generation. OWP industry is a relative new industry, both globally speaking and in the Scandinavian context. None of the highly aggregated industry sectors in the MRIO model are representative enough for modelling offshore wind electricity generation. The original domestic electricity sectors were not considered representative for electricity from OWP; hence direct disaggregation of the electricity sectors was considered too inaccurate. It was therefore chosen to extend the MRIO system with a foreground system including the most important components and materials needed for offshore wind electricity generation. This includes the key components and categories included in an average OWF, and the most important materials used in the wind farm components. This section gives a presentation of the assumptions, inventories and procedures applied for developing the foreground system.

As previously explained, in this study an analysis of OWP production in the Scandinavian countries Denmark, Sweden and Norway has been performed. Since each of these countries has its distinctive economy described in the background system, the hybridization of the system was chosen to be done specifically for each country. This resulted in a hybrid system containing three foreground systems. The real structure of the flow matrix A can be found in Appendix B, Figure 32. The foreground system A_{ff} was assumed similar for all three countries, since this matrix contains the parameters of the Scandinavian case study wind farm. The purchases from the background system to the foreground system and conversely, A_{bf} and A_{fb}, are specific for each country since these matrices depend on the characteristic of the country’s background economy and each country’s scenario for OWP installation. For simplification the process of adjusting the MRIO model will however be explained by a system containing only one domestic country, denoted C, with one foreground system. The other regions will be merged into one region denoted *Rest of the World* (ROW). The approach will in principle be the same when operating with more than one foreground system. Figure 11 shows the simplified structure of the hybrid system.

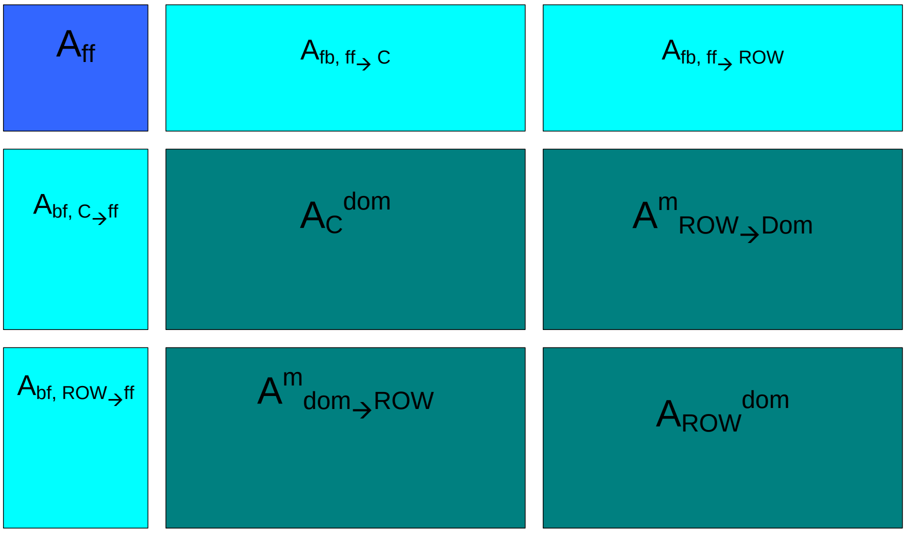

Figure 11: Simplified structure of hybrid system

5.5.1 Foreground system matrix A_{ff}

The list in Table 7 shows the categories included in the foreground system and their units. The flows within the foreground sector were set according to the data given in section 3.3. The complete foreground system A_{ff} can be found in Appendix B, Figure 32, where $a_{ij,ff}$ indicates the material flow from the foreground system sector *i* to the foreground system sector *j*.

The last foreground sector, *Offshore wind electricity generation*, brings together the correct amount of each wind farm sub-sector in order to produce one kWh of electricity, so that the total inputs to this sector corresponds to a share of all life time inputs to a complete wind farm. The input from each sub-sector was calculated by dividing the number of units needed for one case study wind farm by the total life time wind farm production, so that the element $a_{i,15}$ gives

$$\frac{units\ of\ sector\ 1\ needed\ per\ wind\ farm}{GWh\ produced\ during\ WF\ life\ time}.$$

Table 7: The categories of the foreground system and their units.

	Category name	Unit
1.	Copper	[ton]
2.	Aluminium	[ton]
3.	Lead	[ton]
4.	Steel	[ton]
5.	Glass fiber	[ton]
6.	Rotor	[p]
7.	Nacelle	[p]
8.	Tower	[p]
9.	Cable system	[p]
10.	Substations	[p]
11.	Ballast and mooring	[p]
12.	Installation and dismantling	[one case study wind farm]
13.	Operation and maintenance	[one case study wind farm]
14.	Other capital costs	[one case study wind farm]
15.	Offshore wind electricity generation	[kWh]

5.5.2 Purchases from background system to foreground system, A_{bf}

The purchase from the background system to each sub-sector in the foreground system was modeled using the NACE sector from the background system that included the sub sector of interest. The foreground system sectors and the corresponding NACE sectors are given in Table 16 in Appendix B. As a starting point the foreground sectors were assumed to apply the same technology and hence the same distribution of the inter-industrial inputs as the parent sector in the background system. Each column in A_{bf} was hence scaled according to its parent sector so that the sum of all purchases to the sector from the background system plus the total value added was equal to the unit price of the sector. Mathematically, for a given foreground sector, $\tilde{s}$, its parent background sector s, with background system dimension n, background sector total value added vector VA_b and the foreground system price vector p^{unit}, this gives:

$$a_{bf,i\to\tilde{s}} = a_{bb,i\to s}\frac{p^{unit}(\tilde{s})}{\sum_{i=1}^{n} a_{bf,i\to s}+VA_b(s)} \qquad (34)$$

and

$$VA_{\tilde{s}} = VA_s \frac{p^{unit}(\tilde{s})}{\sum_{i=1}^{n} a_{bf,i\to s} + VA_b(s)} \tag{35}$$

Which results in the following relation:

$$\sum_{i=1}^{n} a_{bf,i\to\tilde{s}} + VA_{\tilde{s}} = p_{\tilde{s}}^{unit} \tag{36}$$

There were also made some additional adaptations in order to adjust the sectors. For instance the purchase from the background sectors "Basic metals" and "Metals nec" to the wind farm components were set to zero, since the metals in the foreground system were used as metal inputs. The direct emissions from the five material sectors in the foreground system were found specifically for each material, instead of using the average value from the parent background sector. This data was provided by the Ecoinvent database (Frischknecht and Jungbluth 2007). Figure 12 shows a simplified explanation of how each of the A_{bf} was estimated by its corresponding background sector, with the conversion ratio

$$\text{k} = \frac{p^{unit}(\tilde{s})}{\sum_{i=1}^{n} a_{bf,i\to s} + VA_b(s)} \tag{37}$$

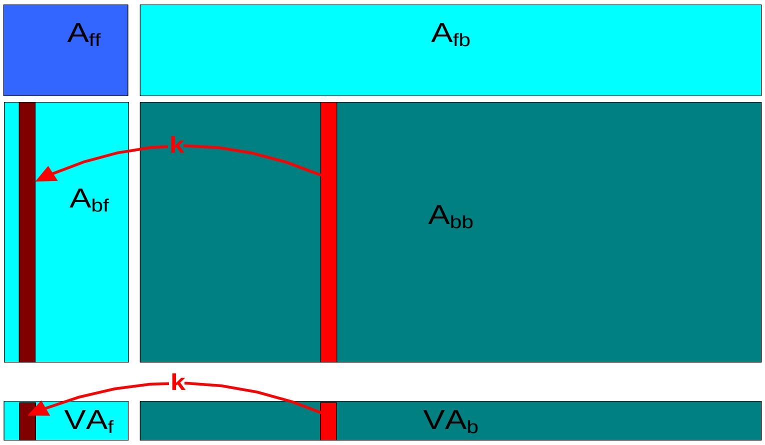

Figure 12: How the modeling of purchases from background to foreground system was done.

5.5.3 Purchases from foreground system to background system, A_{fb}

The only sector in the foreground system that potentially will have sales to the background system is the sector giving kWh of offshore wind electricity generation. For the baseline scenario the OWP output was assumed to be zero, hence both $\boldsymbol{A_{fb}}$ and the final demand for OWP is zero. This resulted in a base case technology matrix, **A**, and a final demand vector **Y** with the following structures:

$$A_{baseline} = \begin{bmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{bmatrix} \qquad Y_{baseline} = \begin{bmatrix} 0 \\ Y_b \end{bmatrix} \tag{38}$$

5.6 Scenario modeling

The scenario analysis of wind electricity generation was done by changing the electricity mixes in the technology matrix **A** and in the final demand vector, **Y**. This was done by adding sales from foreground system sector 15 (*Offshore wind electricity generation [kWh]*) to the background economy. Correspondingly, the sales from electricity from non-renewable energy sources in the background system were phased out in the following prioritized order:

1. Sector 32[9] - Electricity from coal
2. Sector 35 - Electricity from petroleum and nec.
3. Sector 34 – Electricity from natural gas
4. Sector 33 – Electricity from nuclear power

The original total output from the different electricity sectors was calculated using the total output vector x. Changing the electricity mixes in the domestic country was set to first priority. If all the domestic electricity from non-renewables were phased out and replaced by OWP, and the total wind power production had not yet reached the desired scenario level, the wind power was exported. This was done according to the export shares discussed in Chapter 4. The modeling of wind power implementation in the importing countries was done in the same manner as for the domestic wind power implementation. Since the foreground system is given in physical values, and the background economy in monetary values, a price vector for the different countries' electricity mixes was used to convert between [M€/M€] and [kWh/M€]. Figure 13 shows the principle of the process of implementing OWP into the economy. The foreground system is purchasing electricity from the background economy; hence the same procedure was done for the electricity sectors in A_{bf} as for the background economy.

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[9] These sector numbers refer to the 64 sectors used in the MRIO system, with disaggregated electricity sectors.

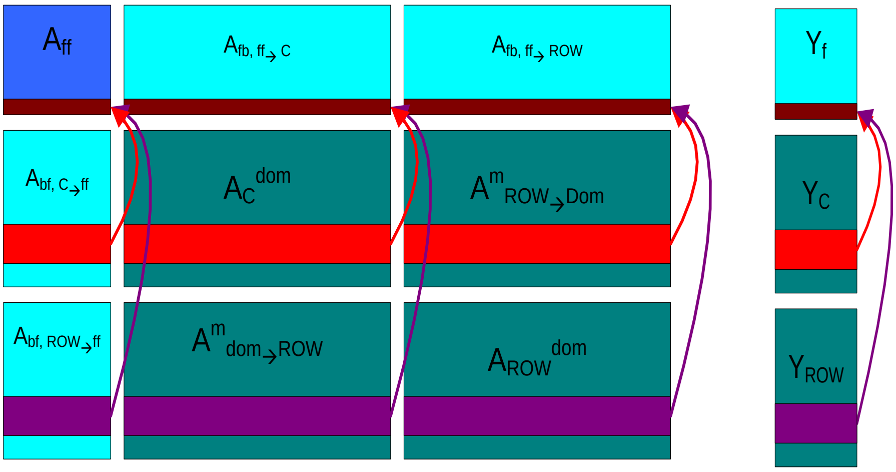

Figure 13: Diagram of the process of replacing non-renewable electricity sources with OWP.

Chapter 6

Results

6.1 Offshore wind power on per-unit basis

In order to analyze the environmental consequences caused by one unit demand of OWP, the unit demand vector y_{unit} was defined, containing the demand of 1 kWh of wind power electricity and zeros for all other industries. The emission from each industry per kWh of wind power output was then calculated from equation (23) in section 2.4.

$$\mathrm{e}= s \cdot (I - A)^{-1} \cdot y_{unit} = s \cdot L \cdot y_{unit}$$

By this the total emission from one kWh of wind power was found by summing the elements of the resulting emission vector e. The resulting emissions distributed over stressor categories are shown in Table 8. The global warming potential was calculated from the greenhouse gases methane, carbon dioxide and nitrous oxide[10]. The resulting contribution from the different stressors was compared both to the per-unit emissions from a 2 MW offshore wind turbine from the Ecoinvent database, and to the emissions associated with 1 kWh output of coal power, based on production average for Nordic countries, provided by Ecoinvent. The results are presented in Figure 8. This shows that the per-unit emissions from the case study wind farm are in the same order of magnitude as the emissions from the ecoinvent wind turbine, broadly speaking. Some stressor categories were however far off, particularly the stressors NMVOC and CO, where the case study wind power came out worse than the coal power average. This variance will be discussed in chapter 7. As far as the global warming potential is concerned, there is good correlation between the two studies, especially in terms of CO_2. The Ecoinvent wind farm emits 10% less GWP than the Scandinavian production average. This is as expected due to a broader system boundary for the EEIO-LCA, recording more complete emission flows.

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[10] A GWP time horizon of 100 years is chosen, with the following GWP intensities: Carbondioxide: 1, methane: 25, nitrious oxide: 298

In this study the focus is set on global warming potential, hence the other stressors will not be included in the further analysis. This is chosen because of the big relevance of greenhouse gases in the context of renewable energy sources.

Table 8: Emissions per unit wind electricity output

	Scandinavian prod. average	**Offshore WT, Ecoinvent**	**Coal Power, NORDEL[11]**	**Denmark**	**Norway**	**Sweden**
GWP	**16.5**	**14.6**	**957**	**17.8**	**16.3**	**15.4**
CH_4(mg/kWh)	97.0	36	4 018	130	71	64
CO_2 (g/kWh)	15.1	13.6	854	14.0	13.8	13.2
N_2O (mg/kWh)	2.9	0.5	36	2.6	2.8	2.4
NH_3 (mg/kWh)	3.3	0.8	21	4.3	3	2.5
NO_x (ug/kWh)	50	34	852	52	51	48
CO (mg/kWh)	474	76	167	362	574	486
NMVOC (mg/kWh)	50	7	36	43	64	44
SO_x (mg/kWh)	67.7	39	39	69	66	68

6.1.1 Emission broken down on industries

A breakdown of the per-unit emission[12] of GWP into sub processes was done using the emission vector e. Figure 14 shows the emission breakdown of one kWh output of OWP. This shows that metal refining contributes considerably to the overall emissions, accounting for more than 30 % of the total emissions. The biggest variation between the three countries is the emission caused by electricity use. Due to the high share of hydropower in the Norwegian electricity mix Norway has the lowest emissions caused by electricity use. Denmark's high share of coal power in the electricity mix results in higher emissions. As a total, the Swedish wind electricity production results in the lowest emissions per kWh. The difference in emissions is distributed relatively equal over the different components. The reason why the Swedish production comes out best in terms of GWP emissions is discussed more thoroughly in section 6.1.3.

When breaking down the emissions caused by metal refining for Norwegian wind power production it is clear that the most emission intensive process is the

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[11] Nordic Countries Power Association

[12] Note that the term "emission" will from now on exclusively denote emissions of green house gases, measured in Global Warming Potential (GWP), if nothing else is specified.

processing of steel, which accounts for more than 60% of the metal emission, and 18% of the total emission. This is not surprising, due to the big amount of steel needed in the wind farm production process. The emission contribution from copper production is also considerable, 11.8% of the metal emissions and 3.5% of the total. This is mostly due to the high quantity of copper needed in the cables, amounting to more than 30% of the total cable mass. The contribution from the aluminium and lead industries was small, only 0.3% and 0.1% of the total emission, respectively. It is worth noting that the emissions from the basic metal sectors in the background system, accounting for 25.6% of the total metal emissions, may also include some of the metals studied in the foreground system, hence the impacts from producing these metals may be bigger than as proposed in this study.

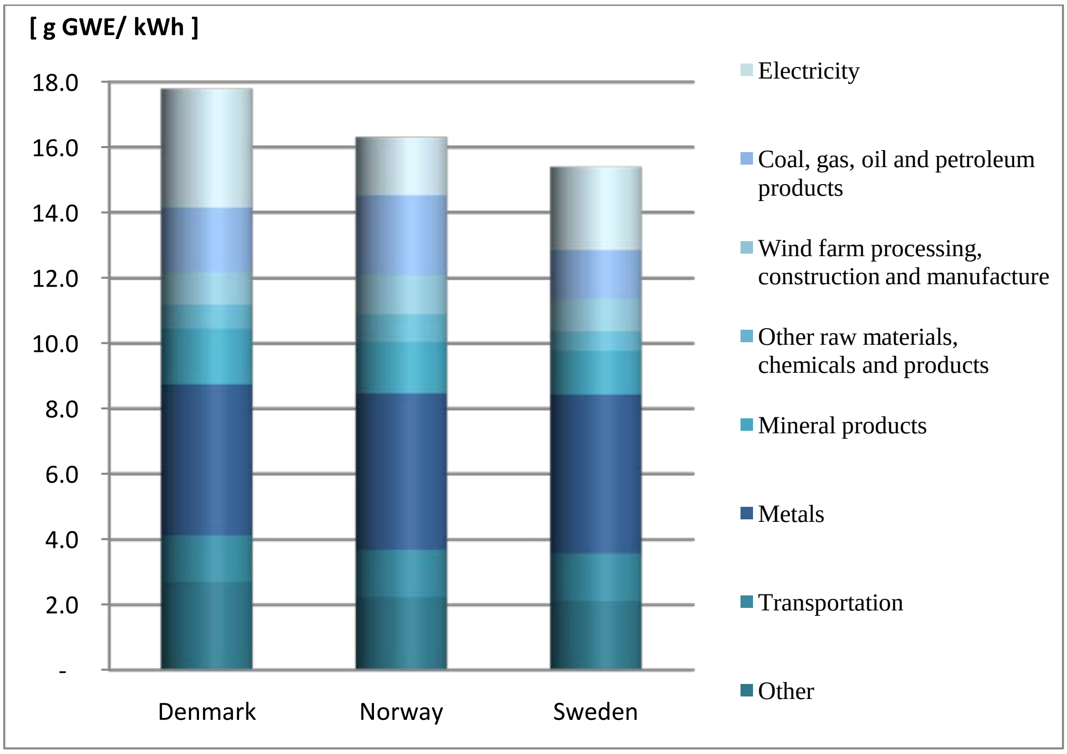

Figure 14: Emissions from producing one kWh of wind energy broken down on industry sector

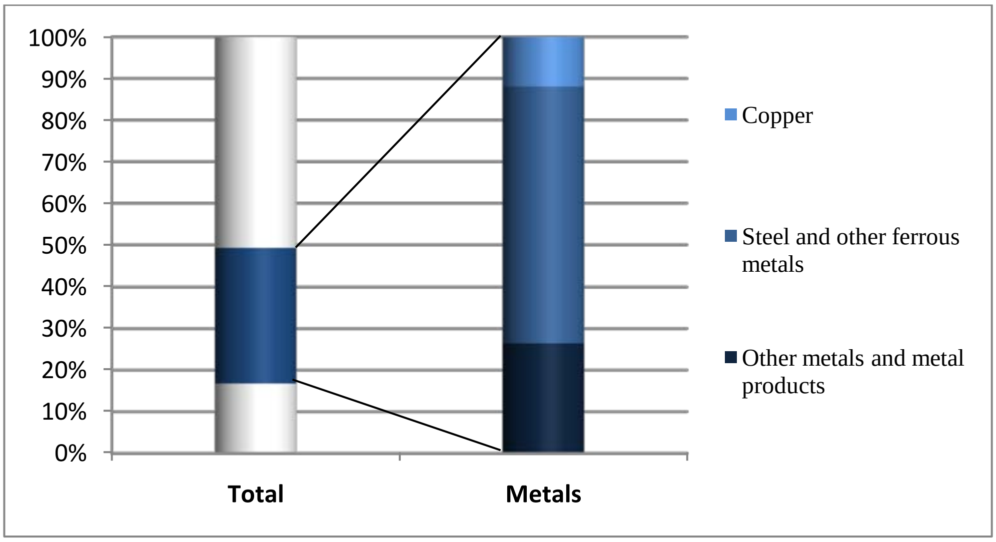

Figure 15: Emission distribution for the metal producing sectors

6.1.2 Emissions broken down on wind farm components

In order to understand which of the wind farm components that contributes most to the total impact a contribution analysis of the different wind farm components was performed. The emissions per unit output of each industry can be found from equation (23) by defining a Y-vector containing one unit demand of all industries.

$$e = f \cdot L \cdot \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \quad \Leftrightarrow \quad e = f \cdot L$$

The total per-unit emissions for the different components in the foreground system were found and thereafter adjusted to the correct amount used in the case study wind farm. For instance, the per-unit emissions of producing one wind tower were multiplied with 60 towers per wind farm, while the emissions from producing one substation were multiplied with two substations per wind farm. After having calculated the total emissions per wind farm, the emissions per produced kWh were calculated by dividing the total wind farm emissions by the total life-time electricity production. The resulting emission broken down on wind farm component is shown in Figure 16.

As can be seen in Figure 16, most of the emissions are generated in the manufacturing phase. The most emission intensive processes during the wind farm life time are the production of the wind turbines and production of the cable systems. The manufacturing of the wind power plants accounts for almost half of the total emission. The operational time of the wind farm, including maintenance work, is responsible for less than 17% of the total emissions. With close to zero direct emissions and no fuel consumption wind energy has low emission intensity when the wind farm is built.

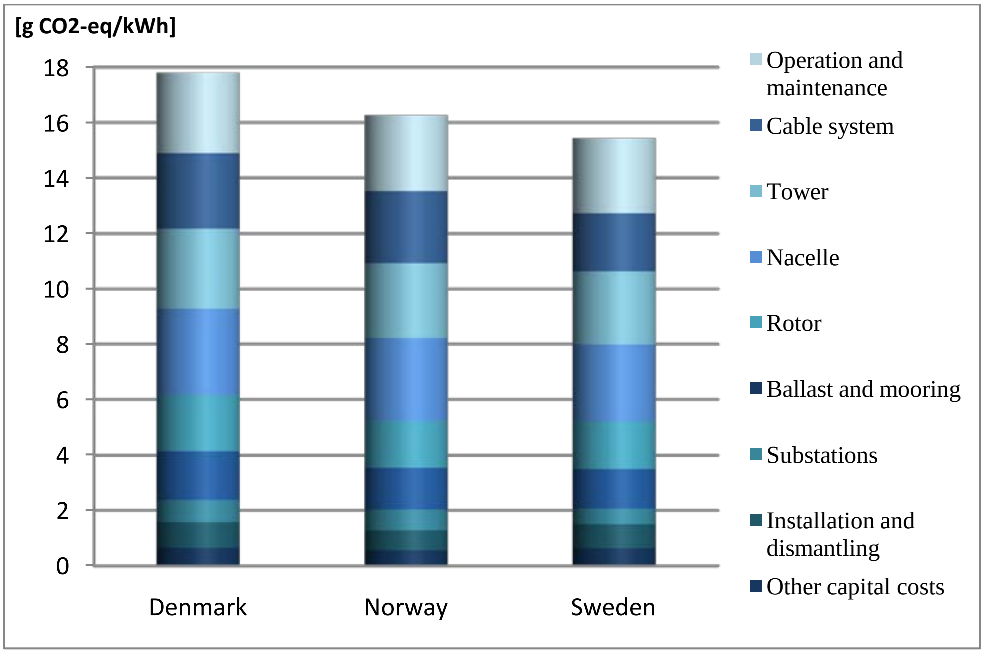

Figure 16: Emissions broken down on wind farm components

6.1.3 Emission embodied in trade (EET)

The methodology relied on when calculating the Emission Embodied in Trade is presented more thoroughly in section 2.4. When studying the inter-industrial input needed to produce one unit output of offshore wind electricity broken down on region, one can see that almost 80% of the industrial input is from domestic industries. Other countries that hold considerable shares of the input are Germany, the Scandinavian countries, UK, China, France and Italy. The percentage breakdown of emissions over regions is shown in Figure 17. The emission from domestic industries is relatively low, when the high share of domestic industrial input is taken into account. Nevertheless, it amounts to more than 40% of the total emissions. The distribution of emissions over regions differs somewhat from the distribution of inter-industrial inputs. Even though the input from other regions than Europe accounts for less than 10% of the total input, the emission accounts for more than 30% of the total. This could be due to more emission intensive industries in these regions. The emission distribution over regions is quite similar for the Scandinavian countries. This implies quite similar trade patterns for the

Scandinavian countries. However, when studying the emissions embodied in imports (EEI) broken down on industry

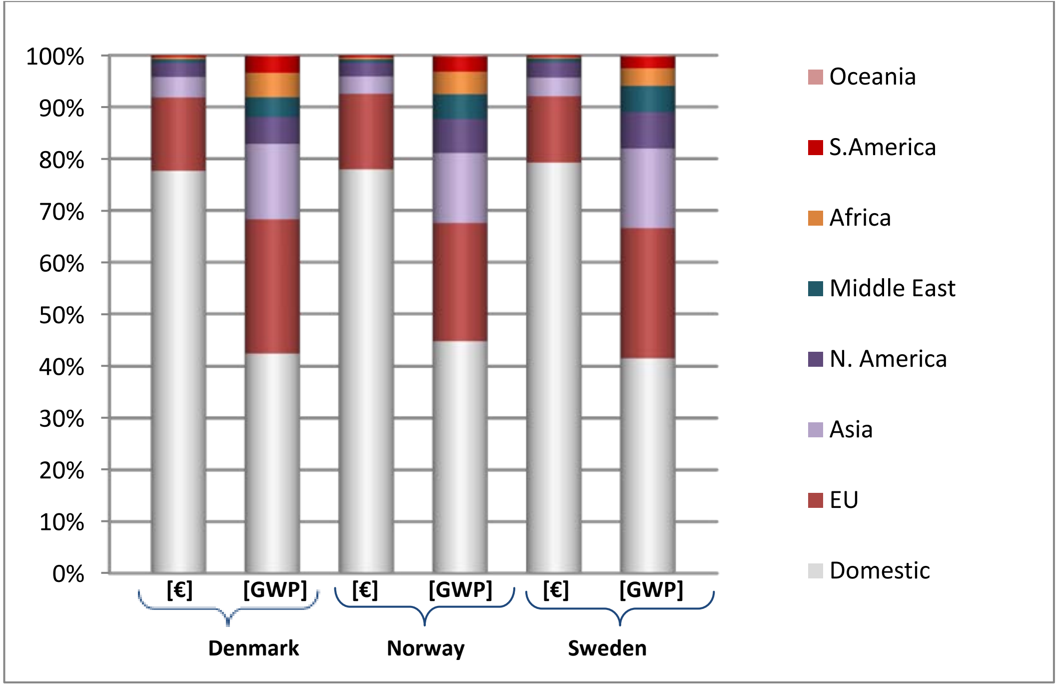

Figure 17: Regional shares of the industrial input and corresponding emissions

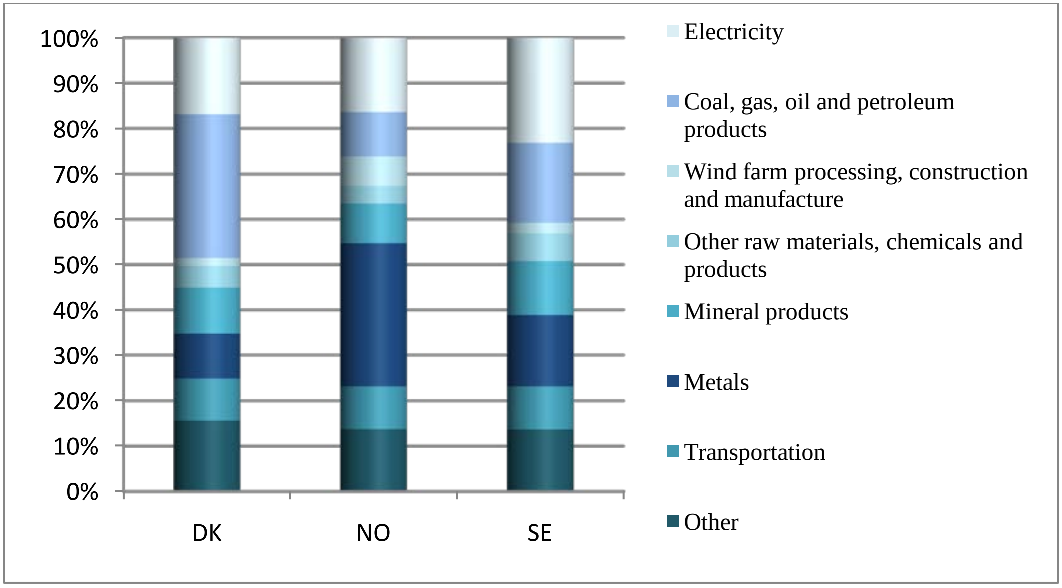

Figure 18: Emissions Embodied in Import broken down on industries.

sectors, as shown in Figure 18 one can see that the import distribution differ highly. Norway has a many times higher share of metal import than Denmark and Sweden, and Denmark has considerable higher emissions caused by import of fossil fuels. This gives indications of some of the characteristics of the different Scandinavian economies. Almost half of the Danish electricity mix is from coal power, and coal imports could hence contribute considerably to the import profile. Norway will according to this model evidently import more metal than the two other countries. This will be discussed more thoroughly below.

As proposed previously, Norwegian wind electricity generation results in 0.9 g/kWh higher GWP emissions than the Swedish, despite of the high share of electricity from renewable energy in the Norwegian electricity mix, outweighing this a little. Also, it is worth noting that Norway comes out worst in terms of CO_2emissions, even though Denmark reach the highest value of GWP due to significantly higher methane emissions. The slight difference between the countries in terms of CO_2 emissions could however be considered disregarded due to the elements of uncertainty, which will be discussed more thoroughly in Chapter 7. Nevertheless, a more thoroughly study of the economical and environmental flows was made in order to explain this somehow unexpected result. Figure 17 shows that Sweden has the highest share of domestic industry input, and it was chosen to look more closely into the trade patterns associated with wind power industry. When studying the emission contribution broken down on industries in Figure 14 in section 6.1.1 it is clear that direct and indirect emission from the metal industries have a considerable contribution to the overall emission. It was therefore chosen to do a more detailed study of the trade patterns in the metal sectors. Since all metal sectors in the foreground system were estimated from the common industry sector “basic metals”, it was chosen to perform a contribution analysis for this background sector in specific. When building the hybrid model the metal sectors in the foreground system were given process-specific direct emissions similar for all three countries for simplification. The contribution analysis was therefore performed by studying only the indirect emissions.

The inter-industrial inputs to the metal sector were found by studying the Leontief inverse. The monetary input per unit monetary output turned out quite similar for the three countries, amounting to around 1.8 €/€. The first step towards achieving an understanding of the trade patterns of the Scandinavian metal industries was to study the inputs to the domestic industry from other regions’ metal industries[13], since this gives a good indication of how big share of the metal that is produced

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[13] This industries included was the EU sector “Manufacturing of basic metals” and the ROW sector “Metals nec”.

domestically. Figure 19 shows the regional percentage distribution of the metal inputs to the metal industries. Please mark that the vertical axis is set to start at a 75% share, this to enable a more thoroughly study of the import shares.

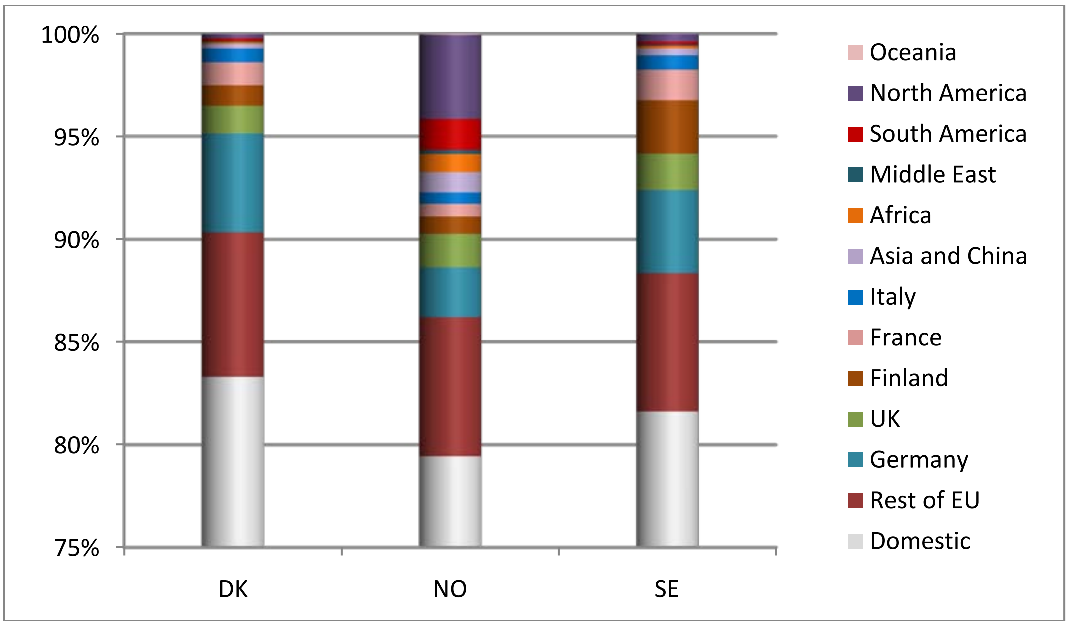

Figure 19: Distribution of import from other countries' metal industries to Scandinavian metal industries.

This representation shows that Denmark has the biggest share of input from domestic metal industries of 83%, followed by Sweden at 82% and Norway at 79%. The attention is drawn to the high share of Norwegian import from the North American metal industry, and it is clear Norway also has higher input shares from regions outside Europe; South America, Asia and Africa. Sweden and Denmark shares higher inputs from European countries like Germany, Finland and France than what is the case for Norway.

After evaluating the trade mix of metals into the metal industry the regional distribution of emissions were studied. All inter-industrial inputs were now included in order to capture the total picture. In Figure 20, the graph to the left illustrates the regional share of the import flows to the metal sector, given in [M€/M€], and the right graph illustrates the corresponding EEI for the three countries, given in [ktons CO_2-eq./M€]. This shows that the EEI are substantially higher for the Norwegian metal industry compared to the Danish and Swedish. Denmark and Sweden are benefiting in terms of lower emissions because of a big import share from Europe, while almost half of the Norwegian import originate from regions outside Europe. 46% of the EEI to the Norwegian metal industry stem from other metal industries. Another sector dominating the EEI to the Norwegian metal sector is the electricity sector, contributing to 29% of the total EEI. One could suspect a more emission intensive import from countries outside the EU into the Norwegian economy than what is the case for Denmark and Sweden. Denmark has a considerable share of import from China and rest of Asia, and higher emissions could be expected from these inputs. However, by comparing Figure 20 and Figure 18 it is clear that a big share of the Norwegian import is from the metal industry. Metal processing is energy intensive, hence metal imports from regions with an electricity mix consisting in a high share of fossil fuels could be more emission intensive than other imports from the same region.

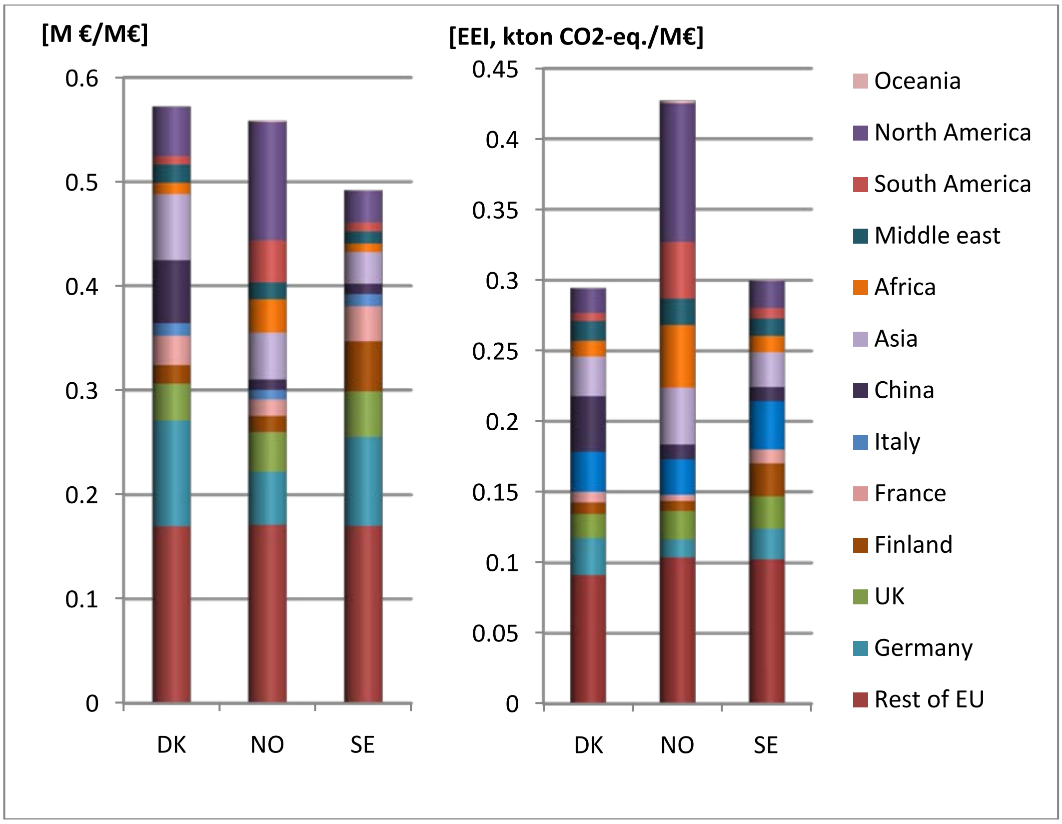

Figure 20: The non-domestic inter-industrial input to the metal sector and the corresponding emissions

6.1.4 Tier expansion analysis

The direct emission from fulfilling a final demand of wind electricity output is approximately equal to zero. However, as proposed previously in this chapter, wind electricity is indirectly responsible for emissions, due to the need for building the wind farm, operation and maintenance and so on. As presented in section 2.4 it is possible to evaluate the indirect emission from wind electricity associated with each "round" of production down the value chain using *tier expansion analysis*. The methodology of tier expansion analysis is presented more thoroughly in section 2.4. The tier analysis of OWP production was compared with the tier expansion of Danish coal power. Figure 21 shows the two tier expansions, with tier number on the x-axis and percentage accumulated emissions on the y-axis. As "Tier 0" is equivalent to the direct emissions, the tier expansion shows that almost 90% of the emissions from coal power occur as direct emissions, while the direct emission from wind power is zero. This evident difference between the two tier expansions is common when comparing renewable and non-renewable energy sources. One needs to go several "production rounds" or "steps" down the value chain of wind power production before most of the emissions are included. 90% of the emissions are not reached before after the 5th tier.[14]

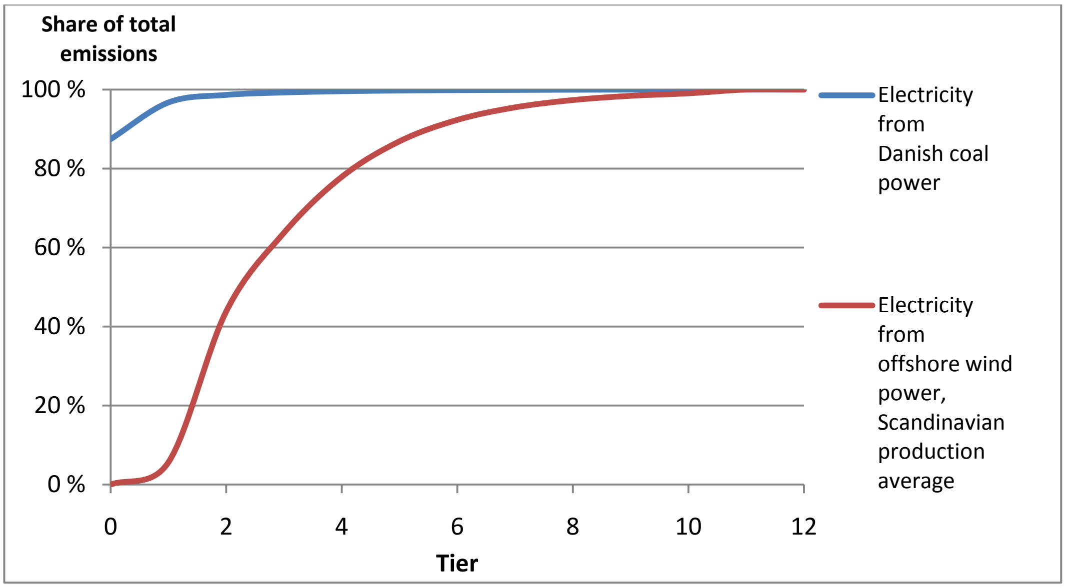

Figure 21: Tier expansion of OWP and electricity from Danish coal power

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[14] It is worth emphasizing that the total emissions from the Danish coal based electricity are 944 CO_2-eq/kWh, compared to less than 20 g/kWh for offshore wind power.

6.2 Scenario results

In order to facilitate the understanding of some of the graphical expansions in this chapter the reader should be aware that some of the graphs are displayed side-by-side. When this is the case the two graphs illustrate the result of a simulation made on both scenarios of OWP installation. The graph on the left will then show the Medium scenario results and the right side graph illustrates the High scenario results.

6.2.1 Norwegian electricity demand

It was chosen to do a more thorough study of the distribution of the electricity demand for the Norwegian economy.

In the base year 2000 the total Norwegian electricity generation was 143 TWh. The electricity demand was dominated by the industry sectors, accounting for more than 60% of the domestic demand, and more than 50% of the total domestic production, which also includes power export. Electricity demand from households was also considerable, amounting to 32% of the domestic electricity demand. In the base year 2000 Norway was a net exporter of power, with an annual net export of around 24TWh, corresponding to around 17% of the total electricity generation. The baseline scenario assumes an increase in electricity demand according to the PRIMES projections for electricity demand as proposed in Figure 6 in section 4.3.1. The total annual electricity generation in the baseline scenario will be 174 TWh in 2020 and 187 TWh in 2030. The Norwegian annual electricity demand will increase correspondingly from 119 TWh in 2000 to 146 TWh and 156 TWh in 2020 and 2030, respectively. It is assumed that the future export shares for the baseline scenario will be the same as for the base year 2000.

Figure 22 shows the Baseline scenario and how this will be affected by the two scenarios for Norwegian wind power generation. The Medium scenario assumes an OWP installation resulting in an annual increase in electricity generation of 1.6 TWh and 8.2 TWh in 2020 and 2030, respectively. By this scenario Norway will increase its power production by 1% in 2020 and 4% in 2030. The High scenario results in a 6.2 TWh and 24.0 TWh annual increase in electricity production, amounting to a 3% and 12% increase in the total production in 2020 and 2030, respectively. The Norwegian OWP generation will mainly act as a supplement to the Norwegian power export. This is due to the high share of hydropower in the Norwegian electricity mix, resulting in an electricity mix consisting almost exclusively in electricity from renewable energy sources. Instead of replacing domestic fossil fuels the Norwegian produced wind power will hence be exported and replace fossil fuels in other countries. This additional power export will for the High scenario increase the Norwegian power export by as much as 73% by 2030.

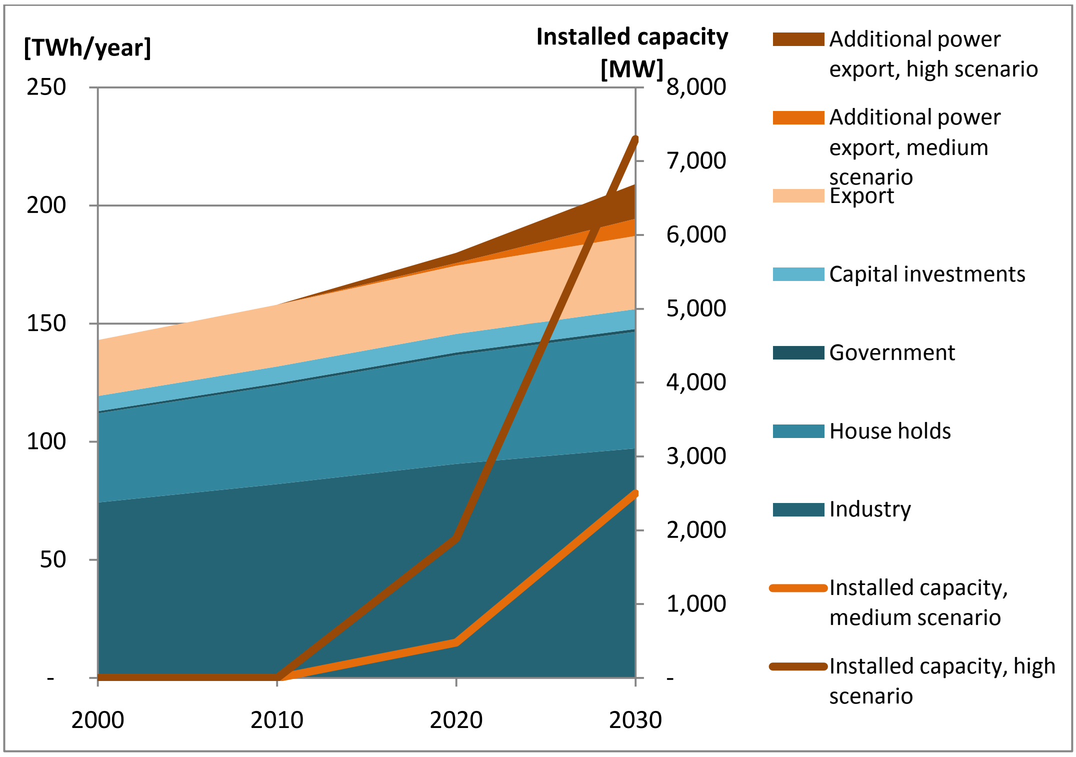

Figure 22: Norwegian electricity distribution with scenarios for wind power generation and export

6.2.2 Study of the change in emissions

In the base year 2000 the total annual Scandinavian emission of GWP was 198 Mtons, of which 65 Mtons originating from the energy sector[15]. The distribution over country is given more specific in Table 9.

Since the baseline scenario assumes no change in technology the electricity mixes will remain unchanged for the scenario period 2000-2030, and the emissions will hence grow proportionally to the increased energy consumption. In the Medium and High scenario an additional offshore wind capacity of 11.8 GW and 22.2 GW is entering the Scandinavian economy by 2030, respectively. This will have considerable effects on the Scandinavian economy in both scenarios. Since the energy sector only accounts for about 33% of the total Scandinavian emissions the

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[15] The term *energy sector* is here defined to include energy transformation and production activities; mines, oil and gas extraction, pipelines, refineries, district heating, power generation and distributed CHP. Transportation is not included.

total percentage emission reduction is only accounting for a 7% and 8% reduction of the annual emission by 2030 for the Medium and High scenario, respectively. The total emission reduction in the energy sector is however considerable, with a 14% and 17% emission decrease. Figure 23 shows the expansion of the annual Scandinavian GWP emissions for all three scenarios. The scenario expansion for each country is also included, where the continuous lines represent the baseline scenario and the dashed and dotted lines represent the emission expansion for the Medium and High scenario, respectively.

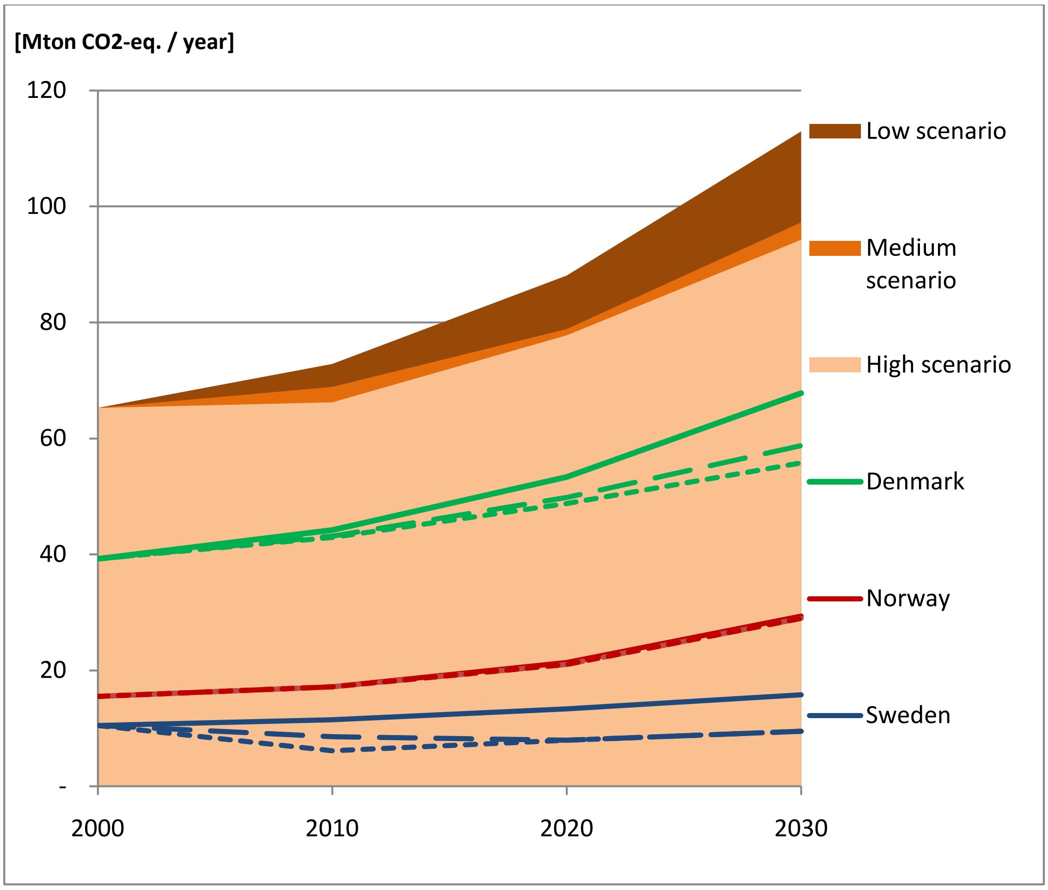

Figure 23: Expansion of future annual GWP emissions generated by the energy sector.

Table 9: The CO_2-distribution over sectors for the Scandinavian countries, base year 2000.

	Total	Denmark	Norway	Sweden
Total (Mton CO_2-eq.)	**198**	**78**	**50**	**71**
Electricity and Steam Production	22%	46%	0%	11%
Energy Branch	11%	5%	30%	4%
Industry	18%	10%	20%	23%
Residential	6%	8%	2%	6%
Tertiary	8%	5%	8%	10%
Transport	37%	27%	40%	45%

In order to evaluate the general effect of the OWP installation the cumulative emission reduction was calculated. The resulting emission broken down on regions is shown in Figure 24. This shows a cumulative emission reduction of 187 and 308 Mtons CO_2-equivalents by 2030 for the Medium and High scenario, respectively.

Most of the emission reduction will take place in Sweden and Denmark. As mentioned above, there is limited capacity for implementing renewable electricity into the Norwegian electricity mix. After increasing the Norwegian renewable share from 99.8 to 100% most of the Norwegian wind power will be exported. In the model it is assumed that 50% of this power will be exported to Sweden and 16% to Denmark. Together with the domestic wind power installation in Sweden and Denmark, this results in a considerable annual supplement of wind power into these countries' electricity mix. The cumulative Swedish emission reduction for the Medium and High scenario will reach 82 Mtons and 139 Mtons in 2030, respectively. Denmark will correspondingly have a cumulative emission reduction of 91 Mtons and 119 Mtons. In the High scenario the Scandinavian offshore wind installation also has a considerable effect on the power importing countries Germany, Netherlands and the UK; a total of 55 Mtons cumulative emission reduction by 2030. This is mainly due to the Norwegian power export.

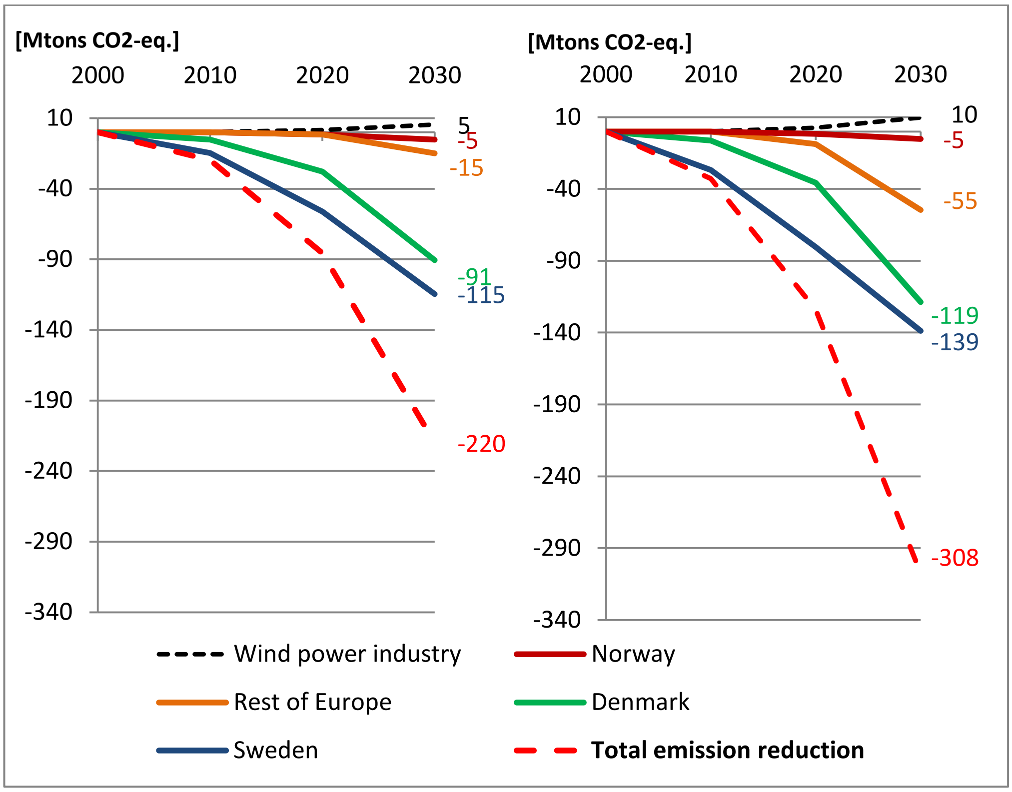

Figure 24: Distribution of change in emissions caused by wind offshore power generation.

In Figure 25 the installed OWP for the two scenarios is broken down on consuming country, and on the type of fossil fuel that is phased out. When studying this in relation to the emission reduction in Figure 24 it is clear that the relation between emission reduction and wind power installation for a country is not necessarily proportional. For the High scenario in 2030, the Swedish OWP implementation is 3.4 times bigger than the Danish, yet the corresponding *annual* emission reduction is actually almost doubled for Denmark[16]. Figure 25 shows that a large share of the wind power generation will be used to phase out nuclear power in the Swedish electricity mix. As described in section 5.6, when all other non-renewable energy sources have been replaced with OWP in a country, the model is set to replace nuclear power. Nuclear power production has a per-unit emission of GWP close to zero, hence the benefit in terms of emission reduction from replacing nuclear power is low or zero.

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[16] This result is not so evident in a cumulative graphical expansion , however it can be qualified by a steeper graph for the Danish expansion than for the Swedish one.

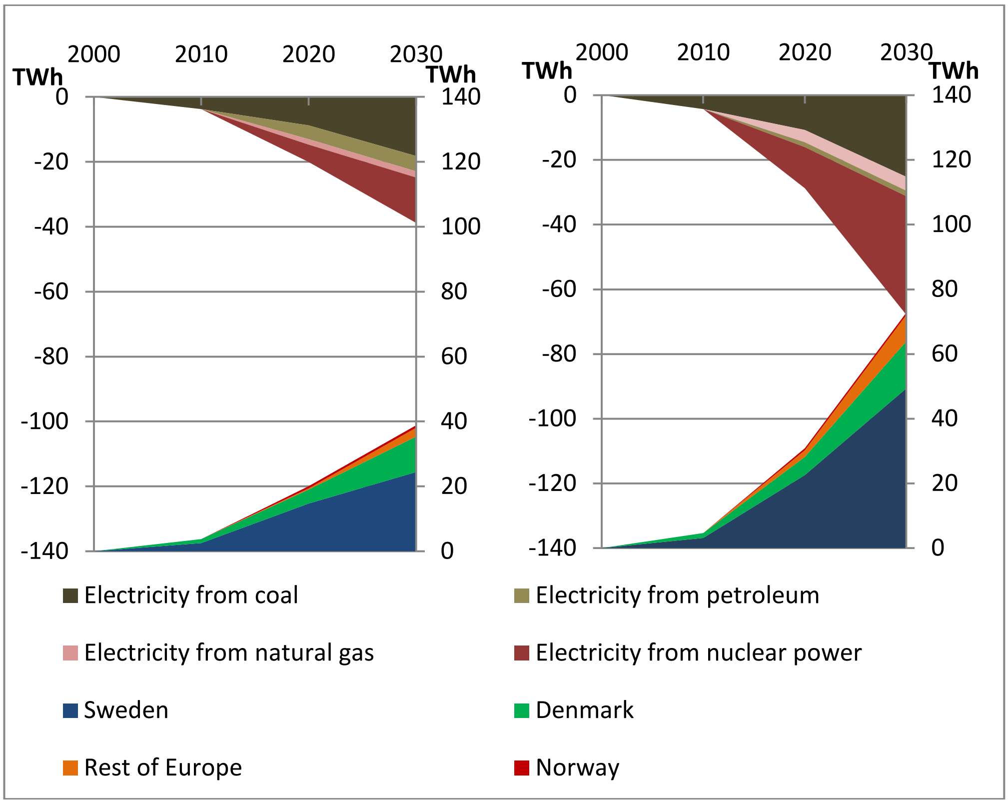

Figure 25: Wind power implementation broken down on country, and the replaced electricity sources.

6.2.3 Change in renewable share

Two factors were considered particularly interesting when studying the change in renewable shares caused by OWP implementation. Firstly, the actual increase in renewable share was studied. Secondly, it was considered interesting to study the effect that the changed domestic electricity mix had on the per-unit emission from wind power production. Figure 26 shows the percentage point increase in renewable shares on the primary axis, and the resulting decrease in per-unit emissions on the secondary axis.

It is not surprising that Denmark and Sweden are benefiting most from the wind power generation in terms of increased share of electricity from renewable energy sources. Even though the offshore wind implementation is bigger for Sweden than for Denmark, Denmark will experience the highest percentage increase in renewable share. Since Denmark has a relatively low electricity demand of 33 TWh, the wind power implementation will be more effective in terms of renewable share for Denmark than for Sweden, with a total electricity demand of 129 TWh. In the Medium scenario Sweden will increase its renewable share by

8.6 pp, while Denmark will experience as much as a 20.4 pp increased renewable share. For Denmark the High scenario involves an increase from the baseline share of 12% renewable electricity to a 38% share in 2030. Correspondingly for Sweden; the renewable electricity share will increase from the baseline share of 56% to a 70% share.

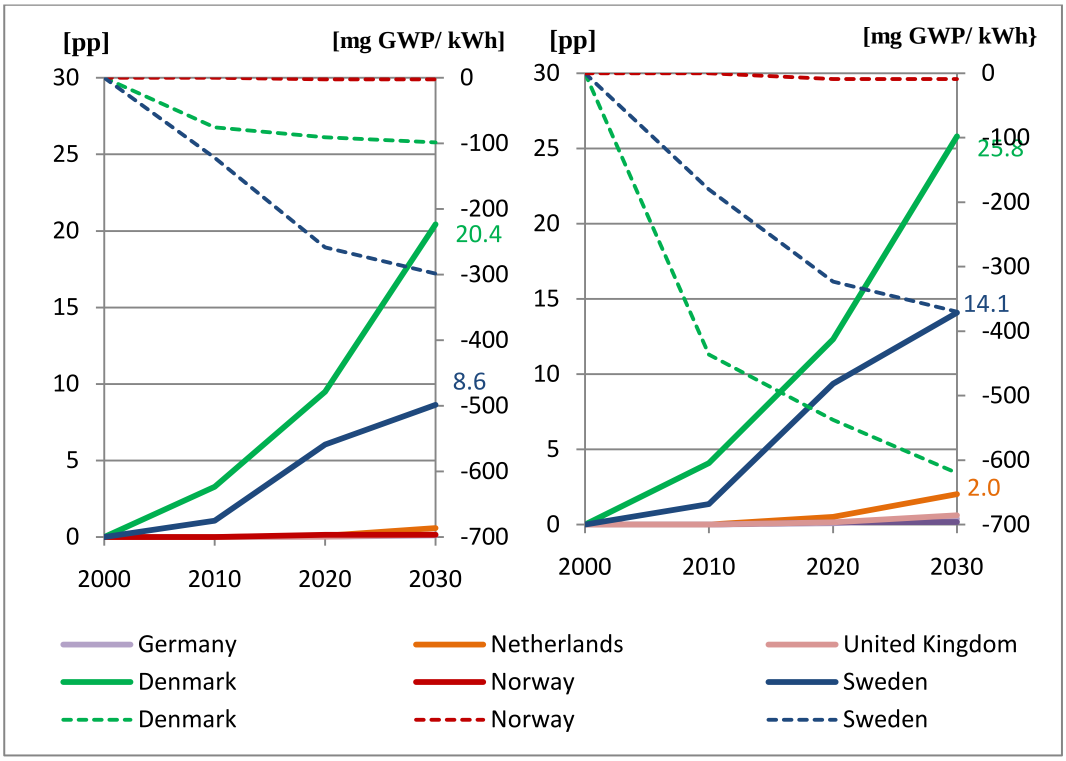

Figure 26: Change in the renewable shares and the corresponding decrease in per-unit emission.

Norway will, as mentioned earlier, not experience any significant increase in its renewable share, but will for both scenarios achieve its maximum possible increase from an original renewable share of 99.8 to an electricity mix of 100% renewable energy. Norway is the only power exporting country in both the Medium and High scenario, so the only non-Scandinavian power importing countries are Germany, UK and the Netherlands. Due to a limited total of power divided over three countries these countries will not increase their renewable shares substantially. The highest increase for these countries will occur in Netherlands, with a 2 percentage point increase for the High scenario. Even though the import of wind power is quite similar for these countries, the import to the Netherlands will be more effective in terms of increase renewable share due to substantially higher electricity consumption in Germany (483 TWh[17]) and UK (329 TWh) than in the Netherlands (98 TWh). For a complete overview of the electricity mixes and the electricity demand for the OWP producing countries, as well as the importing countries, see Table 14 and Table 15 in Appendix A.

When studying the change in per-unit emission from offshore wind electricity generation caused by an increased renewable share in the electricity mixes, it is clear that all three countries will experience a small decrease in per-unit emissions. The Danish decrease in per-unit emission will be biggest, with a maximum decrease of 620 mg CO_2-equivalents per kWh produced, followed by Sweden with a maximum of 370 mg decrease per kWh decrease. This corresponds to a 3.5% and 2.4% emission decrease for Denmark and Sweden, respectively. Norway will not experience particular emission reduction per unit emission due to little increase the domestic renewable share.

6.2.4 Supplementary scenario – Not replacing nuclear power

The influence on the emission reduction by replacing nuclear power was studied more thoroughly by modeling the same scenarios *without* replacing nuclear fuel when all other fossil fuels were replaced in a country. When for instance Sweden has an electricity mix including only renewable and nuclear power, the remaining wind power is exported to other countries according to the producing countries' export patterns. The resulting accumulated emission reduction from these simulations is recreated in Figure 27 below. By this model the Swedish emission reduction remains unchanged, while there is substantial increase in emission reduction for other regions. In the High scenario Denmark will reach a cumulative emission reduction that is 1.8 times higher than when Swedish nuclear power is phased out. Correspondingly, the countries importing Norwegian and Swedish wind power will experience 2.3 times more emission reduction. The power that earlier were used to replace nuclear power in Sweden is now exported to other countries, replacing emission intensive fossil fuels.

The emission reduction is not entirely proportional to the wind power production for this scenario, meaning that the emission reduction does not necessarily double when the production doubles. There are two main reasons for this. First of all, the increase in wind power generation is not linear for the two scenarios. The High scenario is 13% higher than the Medium scenario in 2010, 57% higher in 2020 and doubled (101% higher) in 2030. Secondly, different countries could have different emission intensities of their fossil fuels. When more wind power is exported to countries with a high share of emission intensive electricity like coal-based electricity, the emission reduction per unit of replaced non-renewable

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[17] All given in 2000 value

electricity will be higher. Figure 28 shows how the wind power implementation is distributed over countries, and the breakdown of replaced fossil fuels, both given in TWh. From this scenario Finland will benefit particularly in terms of import of Swedish wind power since 45% of the Swedish export is assumed to be imported into the Finnish electricity market. Denmark is also benefiting from increased import both from Norway and Sweden. In the High scenario more than half of the generated OWP will be implemented into other countries than the producing country.

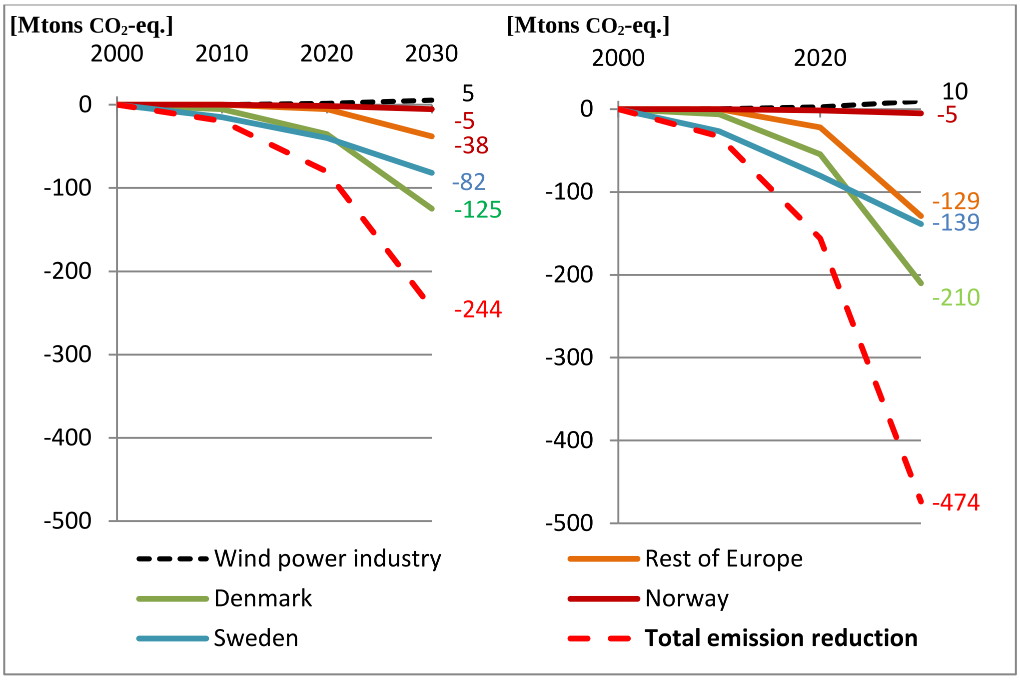

Figure 27: Change in emissions when not replacing nuclear power.

When studying the renewable shares for this scenario, one can see a considerable change in the development of renewable shares. When the OWP was used to replace nuclear power the Swedish increase in renewable share in 2030 was 8.6 and 14.1 pp for the Medium and High scenario, respectively. When the Swedish nuclear power is not phased out the Swedish increase in renewable shares will stabilize on 3.9 pp. After this all the Swedish electricity will originate from renewable energy sources and nuclear power. In this scenario Denmark will experience a substantial increase in renewable shares of 28.7 and as much as 50.0 pp for the Medium and High scenario. The high scenario will hence result in a Danish electricity mix with a 62% renewable share in 2030. Other power importing countries, like Finland and the Netherlands, will also benefit in terms of increased renewable shares, but to a less extent. In the high scenario Finland and the Netherlands will increase their renewable shares by 7.6 and 3.9 pp, respectively.

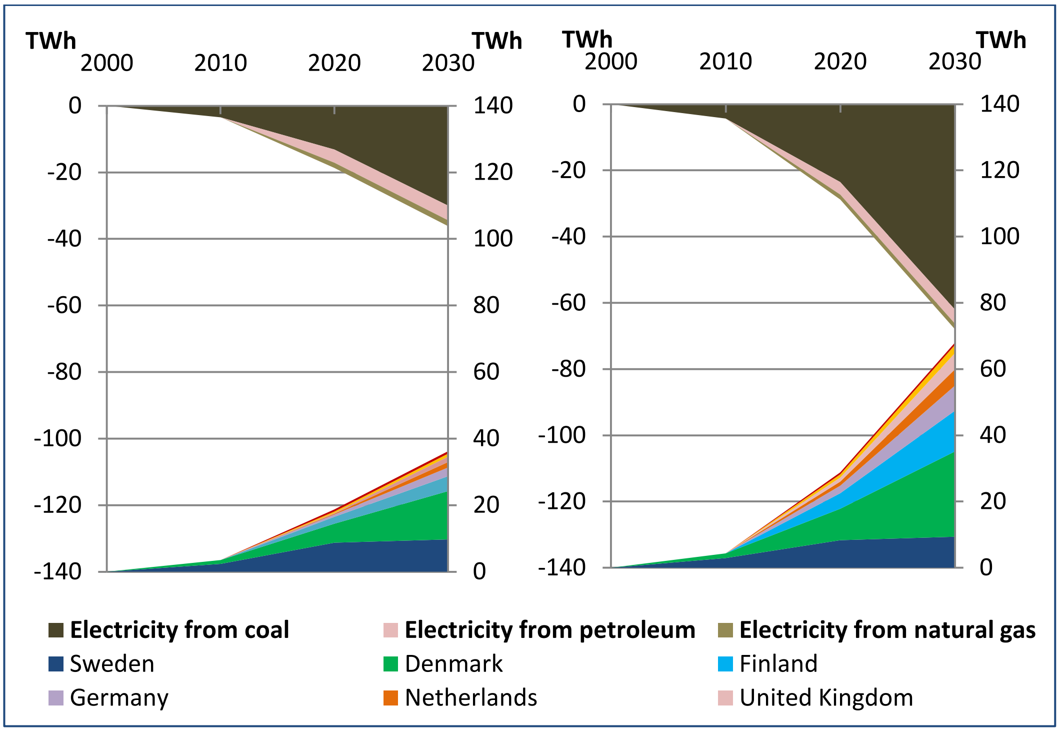

Figure 28: Wind power implementation broken down on country and replaced electricity source.

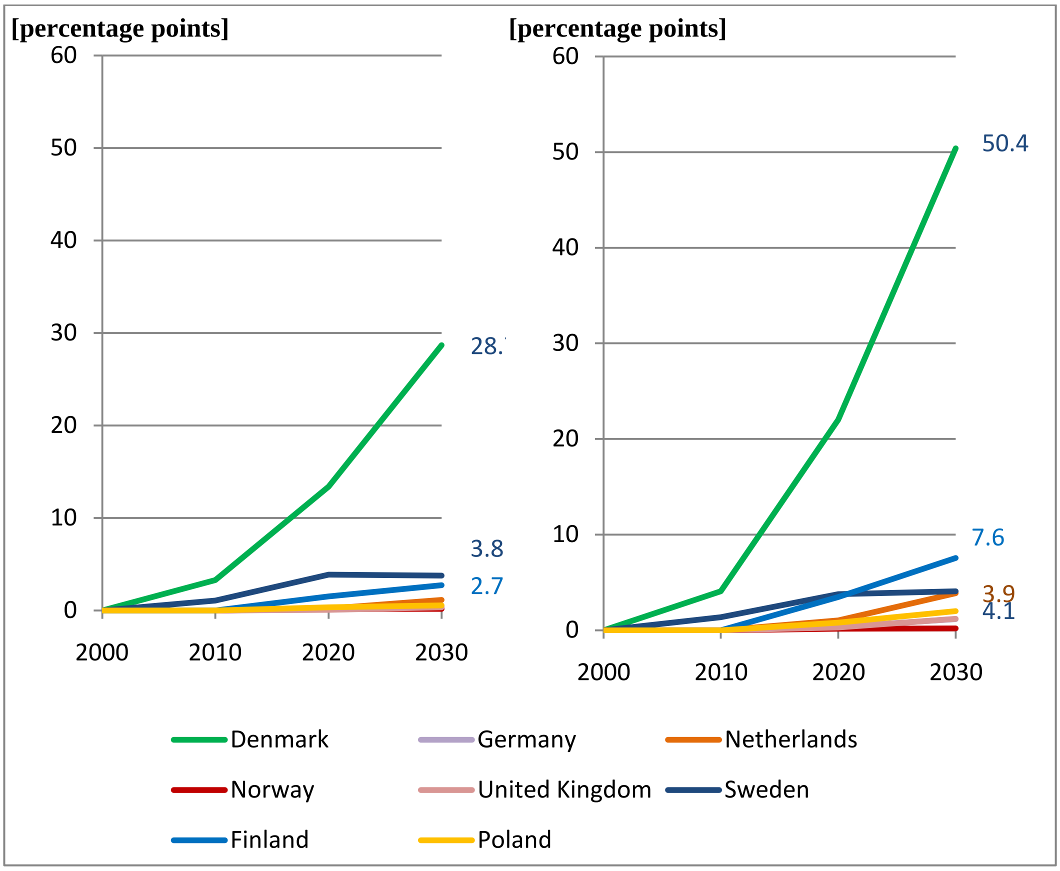

Figure 29: Change in the renewable shares, not replacing nuclear energy.

6.3 Value Added

Additionally to studying the wind power implementation in relation to reduced emissions there was made a study of the change in value added when a new OWP industry were implemented into the Scandinavian economies. The method for calculating the total annual value added for each scenario is analogously to the calculation of total emission; the per-unit emission vector is only replaced by the per-unit value added vector leading to the following expression:

$$V = v \cdot L \cdot y$$

Figure 30 shows the resulting *change in annual value added* for the OWP producing countries, and the summed up change in value added for rest of the world.

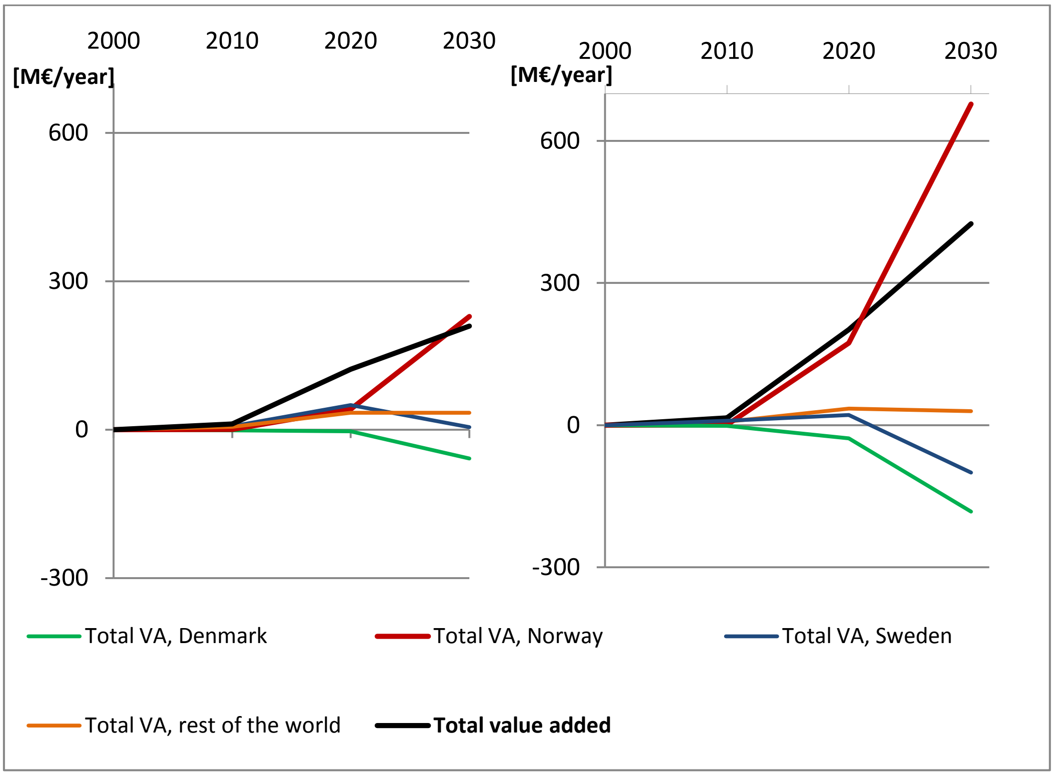

Figure 30: Annual change in value added for the Nordic countries

According to this study there will be a substantial increase in the annual Norwegian value added by implementing a domestic offshore wind industry. Since the Norwegian OWP mostly will be exported, the new industry will act as a supplement to the Norwegian industry, and hence lead to increased value added in the form of wages, profits, taxes, etc. The Swedish and Danish OWP industry, on the other hand, will lead to a small or even negative change in annual value added. Due to these two countries' need for phasing out domestic electricity based on non-renewable energy sources the new industry will not work as a supplement to, but rather as a replacement of other power producing industries. Even though the Danish and Swedish OWP will result in a large increase in annual value added in terms of increased industrial activity, this surplus will be offset or more than offset by the decrease in value added caused by phasing out non-renewable electricity sectors.

By studying the Norwegian annual value added from the implemented offshore wind industry more thoroughly, it is clear that the increase in value added will occur on different levels of the economy. More than half of the increased value added will be a direct result of the wind power industry; which includes production of the wind farm components, operation and maintenance, and installation and dismantling of the wind farm. Additionally to this there will be some increased value added in the other domestic industries that are directly or indirectly affected by the new industry. The highest additional increase in value added will however be in form of financial and business activities and increased activity in service sectors. This will amount to more than 30% of the total increase in the annual value added.

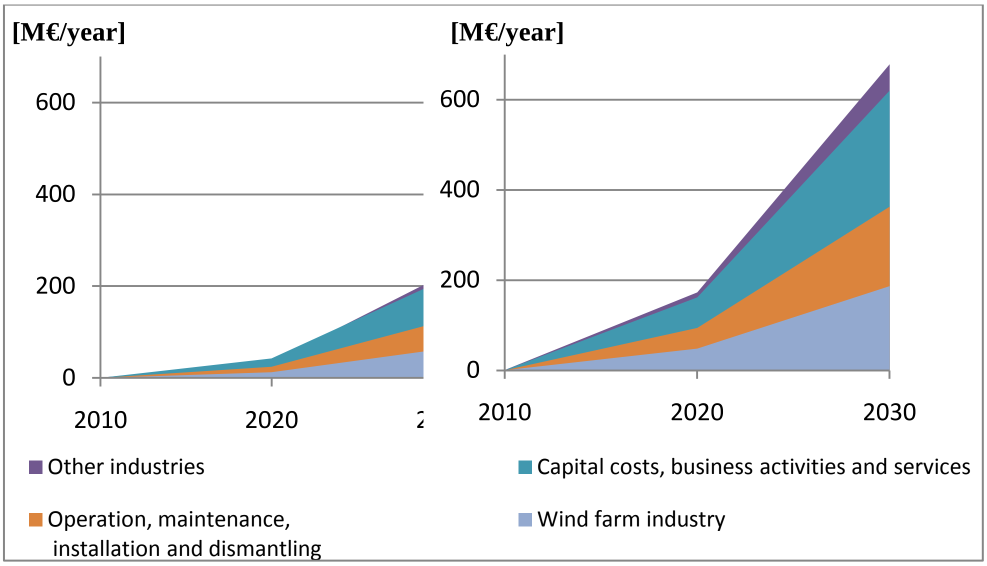

Figure 31: Annual increase in the Norwegian value added broken down on sectors.

Chapter 7

Discussion

In this study a Multi Regional Input Output model was developed on the basis of statistical data. This was done by adapting make and use tables, symmetric input output tables, domestic flows and import flows from the base year 2000. The resulting MRIO system consisted of an inter-industry flow matrix, Z, a value added matrix, v, and a final demand matrix, Y. By this a comprehensive and versatile system was created, covering inter-regional flows between 23 European countries, each with 64 appurtenant industrial sectors, as well as 8 more regions covering the greater part of rest of the world, each region including 62 industry sectors. In order to extend the system to enable environmental studies a stressor matrix, s, was compiled, including the per-unit emission of a selection of stressors per unit of industrial output. After having developed the MRIO database with environmental extensions the system was hybridized in order to perform studies connected to Scandinavian offshore wind power generation in specific. This was done by adding a foreground system including the key components and materials used in a typical Scandinavian wind farm. Industry categories in the inter-industry flow matrix were used as proxies for the foreground system sectors, and adjusted to their purpose with help from price data as well as specific data on the use of some materials.

Since one of the main objectives of the study was to perform an environmental analysis of future scenarios of offshore wind power generation, a baseline scenario within the time frame 2000 to 2030 was created. The baseline scenario assumed no change in the region's technologies and trade patterns, the only parameters assumed to change were the exogenous final demands from the commodities or services constituting the industry sectors. Most of the final demand was modeled to grow in accordance with future projections on gross domestic product (GDP). The future development of the electricity demand was considered vital for the scenario outcome; hence it was chosen to scale the electricity sectors in accordance with projections of future energy demand rather than by GDP projections.

Two scenarios for Scandinavian offshore wind power were generated; a Medium scenario and a High scenario. The scenarios were adapted from various projections of future offshore wind power production provided by reliable sources in the wind power sector. The Medium scenario was an attempt at projecting the most realistic development of the future Scandinavian offshore wind power industry, with a total installed capacity of 11.8 GW by 2030. The High scenario was optimistic; assuming an installed capacity almost doubled with respect to the Medium scenario; assuming 22.2 GW installed capacity by 2030. The main focus of the study was the environmental approach, hence the first priority of the simulations was to track and evaluate environmental impacts. Firstly, the environmental impacts from wind power generation were studied on a per-unit basis. By this a contribution analysis was made, both in terms of emission broken down on industry sectors, as well as the distribution of emissions over wind farm components. Thereafter simulations were run for all three scenarios and the resulting total emission profiles were compared and analyzed.

The environmental impact associated by one unit output of offshore wind power was evaluated for eight different stressors, but the main focus in the analysis was on the global warming potential, which was derived from the stressors methane, carbon dioxide and nitrous oxide. The per-unit emissions of GWP for the Scandinavian production average was found to be 16.5 grams of CO_2 per kWh of electricity produced. The per-unit emission differed little between the countries, and was for all three countries found within an interval of +/- 1.3 grams difference from the average value. When studying the emissions of GWP broken down on industries it was clear that metal processing contributed most to the total emission, accounting to more than 30% of the total. Steel was the dominating metal, contributing to more than 60% of the emissions from the metal industry, followed by copper, responsible for about 13% of the emissions from metals. Another dominating industry was the electricity sector, which was the category with the highest difference between the three countries, due to the countries' highly different electricity mixes. The emissions broken down on wind farm components stated that the sub-process of a wind farm life time with the highest impact was the manufacturing phase, and in particular the production of the wind turbines, accounting to almost half of the total emission. The production of the cable system was also an important contributor to the overall impact. The operational phase of the wind farm accounted for less than 17% of the total emission. This was not surprising, since a low share of impact from the operational phase is a typical characteristic for renewable energy sources. When studying the regional distribution of the emissions one can see that only about 40-45% of the emissions occurred in the domestic country, even though almost 80% of the monetary input flows originated from domestic industries. The remaining input was dominated by other European countries with about 14% of the monetary inputs and about 25%

of the emissions. The regions Asia, Middle East, Africa and South America hold almost negligible monetary inputs of less than 10%, but the resulting emissions amount to as much as 26%. This is a noteworthy result that gives an indication of the variance in the different regions' environmental profiles.

The scenario results stated considerable effects on the Scandinavian emission profiles by implementing offshore wind power into the economies. The annual change in emissions amounted to a 7% and 8% decrease in the total Scandinavian emissions for the Medium and High scenario, respectively. This corresponds to a 14% and 17% decrease in emissions generated by the energy sector. The cumulative value of saved emissions reached as much as 187 and 308 Mtons CO_2-equivalents by 2030 for the two scenarios. Since Norway has an electricity mix consisting in almost exclusively hydropower, the possibility of implementing wind power into the Norwegian electricity market is limited. Most of the Norwegian wind power will be exported according to an assumed Norwegian export share. A big share of the total installed wind power will be consumed by the Swedish economy, due to a big domestic production combined by considerable import from Norway. The biggest emission reduction will take place in Denmark and Sweden, followed by the power importing countries UK, Germany and the Netherlands. In this simulation most of the wind power will be used to replace electricity from coal or nuclear power, and the High scenario will result in as much as a 25.8 and 14.1 percentage point increase in renewable shares for the Danish and Swedish electricity mix by 2030, respectively. A supplementary scenario was studied by running the same simulations without phasing out nuclear power. By doing this, the emission reduction increased dramatically, since the Swedish economy was starting to export its power to countries holding coal-based electricity, like Denmark and Finland. Consequentially this resulted in a smaller increased renewable share for Sweden, and correspondingly a bigger increased renewable share for the power importing countries.

A brief study was performed of the change in value added caused by the offshore wind power producing countries. This study showed a big variation of the change in value added between the countries. Sweden and Denmark will experience no significant increase in value added, and for some scenario years the gross change in value added is negative for these two countries. Norway, on the other hand, will by 2030 increase its annual value added by 230 and 680 M€ for the two scenarios. The Norwegian offshore wind power industry will work as a supplement to the Norwegian economy, creating a net increase in the industrial activity. In Sweden and Denmark, however, increased wind power industry will lead to phasing out of other power industries, which will compensate for the value added caused by the increasing offshore wind power industry.

When comparing the per-unit results with other studies made on wind electricity the values for GWP and CO_2-emissions per unit output were found within the range of expectation. A wind power system is a big and complex system, and the environmental properties strongly depend on parameters like wind farm dimension and characteristics, as well as the chosen system boundary. In order to achieve accurate results detailed data about the wind farm inventories and manufacturing processes are demanded, but this is often hard to obtain. Environmental studies of wind power generation may therefore suffer from rough estimations, and highly different results are found from one study to another. Previous environmental studies of offshore wind power generation report emissions of CO_2-equivalents varying between 5.2 and 18.5 g/kWh. With a resulting Scandinavian production average of 16.5 this study lies in the upper limit of the interval. This outcome is the same as obtained from a life cycle assessment of the Danish wind farm Tunø Knob, a system of ten 500 kW wind turbines completed in 1995 and situated 6 km from shore (Schleisner 2000). Since this study was performed on an existing wind farm the result is considered reliable, which indicates that the results from this study may be quite realistic.

When comparing the results with previous LCA studies one should consider the effect of having extended the system boundary from a relatively limited system boundary used in a traditional LCA, to a complete system of a MRIO model, which in theory covers the whole world. A MRIO model will provide a more complete picture of the system, tracking flows and trade patterns, not only between sectors, but also between regions. For instance, domestic industries with a considerable contribution to the wind farm manufacturing, like for instance the metal industry, are often subject to considerable shares of trade, which could in turn result in considerable shares of emissions embodied in imports to the domestic country. A traditional LCA study makes it difficult to consider these factors on the whole. Due to this a higher result in terms of per-unit emissions could be expected from an EEIO-LCA study than from a traditional LCA study.

The industry flow matrix and the final demand were compiled from domestic flows and import matrices, and the data was provided by reliable sources like Eurostat, the GTAP project, IEA and OANDA, and the data quality of these matrices should be good. There are however some elements of uncertainty that should be considered. In order to obtain the same order of disaggregation between the sectors of the GTAP trade shares and the NACE sectors bridging operations were necessary, and this involved splitting or merging of some sectors. These operations could cause uncertainties, since one has to make assumptions about import shares that may be inaccurate. As for the GTAP data one should mark that the import share from one country to another is assumed identical for all industries within the importing country. This could be a too rough estimate for technologies that differ considerable from the country-average in terms of industrial input and trade patterns. Nevertheless, all these considerations taken into account, the data quality of the industry flow matrix and the final demand is considered satisfactory for this study, which is striving to catch tendencies and hence a general impression of the flows of the global economy.

As far as the stressor vector is concerned, the data quality is considered somehow less accurate. Due to lack of international emission reporting standards, the emission data for the different countries are fluctuating, with highly different orders of dissolution and numbers of stressor. Constructing the emission vector did therefore involve several bridging processes and the use of proxy countries when a country was missing data. Some of the stressor data was however more accessible, especially the CO_2emission. This is reflected in the results when the per-unit emission is compared with wind power data from Ecoinvent. The emission of GWP differs in the order of about 10%, while more uncommon stressors differ highly, like NMVOC; resulting in 38 mg/kWh for this study and 7 mg/kWh for the Ecoinvent data. Since this study was to be focused mainly on global warming potential there was not made any further work in order to track the sources of error. This data should hence be treated carefully.

Broadly speaking a challenge related to the EEIO framework is the restricted data availability. However, in the future standardized reporting systems and more mandatory participation from all countries will help to overcome these limitations. The EXIOPOL project is currently setting up a detailed environmentally extended Input-Output framework, indicating that more accurate models are approaching. Finally the system applied in this study consisted in matrices with more than 2000 row and/or column elements, which renders a complete overview of all data impossible. Even though quality checks were made in order to reveal bugs in the computer algorithms used for the system compilation as well as in the analytical phase, the data may contain sources of error that have not been unmasked. Due to the highly realistic outcome with regard to the global warming potential, the system is still considered reliable for evaluating GWP.

A country's GDP is found by summing the final expenditures of the country's economy, adding the export values and subtracting import expenditures. *Final expenditures* include final consumption by households, government and industry. This shows a close link between a country's GDP and the final consumers' demand of goods and services. By this one could conclude that scaling the final demand according to GDP is a good approach sufficient for the aim of this study. For simplification the industry flow matrix was remained unchanged in the baseline scenario, assuming that the industries' technology will not change between 2000 and 2030. There are some implications regarding this approach, since this makes an assumption of a proportional relationship between the final demand and total industrial input. By this approach a future 10% increase in final demand of a product will result in a 10% increase in industrial inputs to this sector and a 10% increase in emission caused by the demand of the sector. For many industries this will not necessarily be the case. Many technological structures are likely to change in the future, in terms of more efficient material use, more frequent use of recycled material, more efficiency in the transportation sector, and what is most relevant for this study; more efficient energy use. The PRIMES model projects a 1.4% annual increase in energy intensity in the time frame 2005-2030. As for the electricity sector, the future electricity generation plants are expected to yield higher efficiencies and hence lower per-unit emissions (European Commission 2008). Electricity has however a special characteristic in the context of energy efficiency. According to the European Commission (2008) an increased electrification of processes has taken place since 1990 and the share of solid fuels in industrial energy consumption has declined. The market share of electricity in the European industries is hence expected to increase from around 28% to 34% between 2000 and 2030. In other words there are many indications of the future development of the electricity sector that could be considered. All these factors taken into consideration it is hard to predict whether the assumption made in this study yields higher or lower outputs than what will in fact be the case.

The complete system of a wind farm is on the one hand a big and complex system consisting in several parts and processes, which requires a good overview of the general system. On the other hand, a wind farm consists in large amounts of materials, and detailed information about each component and its inventory is crucial for achieving realistic results. Much effort was made in order to build a realistic foreground system. Both the price breakdown of the wind farm components as well as the material used by each component was based on sources that are considered trustworthy. As expounded in 5.5.2 the monetary flows from the background economy to the foreground system were obtained by using background sectors as proxies. Even though the chosen proxy sector was the sector containing the desired product, this approach could involve some uncertainties. When the desired product is not representative for its parent sector in terms of technology or price the approximation may lead to erroneous results. Additionally, a foreground system based on physical units and a background system based on monetary units demands a price vector for the conversion between monetary and physical values. As mentioned, the wind farm price breakdown was considered reliable. The prices for the foreground system material, on the other hand, were more challenging to decide, since the price data differed highly for different sources. The prices were eventually chosen on the basis of the reliability of the references. As the material prices directly influence which amount of material that is included in the wind farm components, the sensitivity of the metal prices, and especially the steel price should be subject to discussion. One should be aware that increasing the steel price by 10% would result in a 10% increased environmental impact from the steel industry, which would imply a 1.8% increase in the total emission of GWP.

In this study there was a need for studying the electricity sectors more thoroughly, and the monetary outputs of electricity were hence converted into physical values before analyzed. The price vector used in the converting process was collected from the International Energy Agency. The MRIO model were compiled assuming homogenous electricity prices within a country, which could be misleading; electricity prices will vary between power companies and the electricity prices are not equal for households and industries. Due to this one should not apply the estimated electricity prices heedlessly. For some countries it was considered more accurate to adjust the electricity outputs according to actual data on electricity consumption provided by reliable sources. This was then done for the base year, and the same adjusting factor was applied for the years 2010-2030, maintaining the ratio of change.

One should be conscious about the fact that the system was modeled in order to study Scandinavian offshore wind power in particular. The development of other electricity sectors was not taken into consideration. Neither offshore wind power development in other countries than the Scandinavian, nor the development of other renewable energy sources has been assessed. By doing this a model is achieved that only takes Scandinavian offshore wind power into account, while all other factors are assumed unchanged. The most interesting scope of the model is therefore not necessarily the total output achieved from the different simulations, but rather the *relative change* between the different scenarios.

Analyses of future wind power scenarios were performed in this study, simulating an additional 11.8 and 22.2 GW of offshore wind power installed in the Scandinavian countries by 2030. One could discuss the likelihood of these scenarios; today the Scandinavian offshore wind industry is limited, with an installed capacity amounting to only 409 and 133 MW in Sweden and Denmark, respectively. Reaching the Medium and High scenario would require the Scandinavian wind power industry to grow 22 and 41 times bigger than today on a limited time interval, which would demand a dramatic growth in the wind power sector. However, big wind farm projects are in fact in progress. For instance, Sweden, Denmark and Germany are currently initiating a joint venture project of building the world's first ocean-based grid in the Kriegers Flak area of the Baltic Sea. The grid involves a comprehensive wind power installation, the total planned capacity reaching 1600MW. If a number of big wind farm projects like the one in Kriegers Flak are carried through this could result in considerable increase in the Scandinavian offshore wind power industry, and the scenario projections could be reached.

As described previously, the EU directive on promotion of energy from renewable sources sets binding targets for the member states in terms of increased renewable share. For Denmark and Sweden this involves an increased renewable share of 13 and 9.2 percentage points (pp). The renewable share is calculated on the basis of the total final energy consumption in a country, and no specific target is set for the electricity sector. In order to evaluate the renewable target in context of the electricity sector it is assumed that the increase in renewable share will be evenly distributed over the energy sectors, and a target of a 13 and 9.2 pp increase in the renewable share of the electricity mix by 2020 is assumed for Denmark and Sweden, respectively. Keeping this in mind it is clear that the Medium scenario does not involve sufficient offshore wind power installation for reaching the renewable target, but reaches only 9.5 and 6.1 pp increase in renewable shares by 2020 for Denmark and Sweden, respectively. For the high scenario Sweden reaches its target with a 9.4 pp increase, and Denmark is close to its target, reaching a 12.3 pp increase. As for the supplementary scenario when nuclear power was not replaced Denmark reaches its targets for both Medium and High scenario, but Sweden fails to reach its renewable target, stagnating on a 3.9 pp increase. From this it can be concluded that the policy for nuclear power is a subject for discussion. This study stated that not replacing nuclear power had an evidently positive effect on the total emission reduction, i.e. it resulted in 30% and 54% higher emission reduction for the Medium and High scenario. Nuclear policy is a somehow controversial topic, and the increasing attention on global warming may increase the debate regarding ranking of priorities; in this case with reducing greenhouse gases on one side, and phasing out nuclear power on the other side.

In the case of Norway, there is some complexity associated with a future offshore wind industry. Firstly, as stressed previously, the Norwegian electricity mix contains almost exclusively of hydropower, and the incentives of investing in renewable energy sources is hence not as urgent as for many other countries. Secondly, there is currently a public discussion in Norway concerning the future of the Norwegian energy-intensive industry. Today, the energy intensive industry benefits from low-priced Norwegian power compared to other European countries. Future projections of Norwegian electricity export give rise to concerns about how the electricity prices will be affected by a closer connection to the European energy market, which is operating with higher electricity prices.

As far as the EU directive is concerned Norway is not yet incorporated in the EU renewable directive; hence the Norwegian renewable target has not yet been set. The target has however been estimated to a 14.5 pp increase in renewable shares (Point Carbon 2008). If this estimation is realistic the target could be challenging to achieve due to certain regulations of the directive set by the European Commission. Firstly, the production of offshore wind power will not count in terms of increased renewable share as long as the energy is exported and not consumed domestically. Secondly, if the domestic renewable target is not met, Norway is not able to sell the wind power with *guarantee of origin*[18]. In other words, if the directive is not adjusted according to the Norwegian somehow unique energy situation Norway must achieve most of its increase in renewable shares from the transport sector or be forced to buy guaranties of origin from other countries.

When that is said, Norway holds an enormous offshore wind power resource that should be exploited. One could argue that a country with such a high potential for producing renewable energy has a responsibility for exploiting these resources. Even though Norway is filled up with electricity from renewable energy sources in form of hydropower it is shown from this study that other countries could benefit considerably from Norwegian offshore wind power industry, which could help them achieve their renewable target. The Nordic countries' access to easily regulated hydro power combined with big investments in wind power could in the future make the countries in the North essential exporters of regulated renewable electricity to rest of Europe, and in this way work as a stabilizer for a future EU power grid based on renewable sources.

7.1 Conclusion

With a business as usual approach to the world's increasing economical growth the global emissions of greenhouse gases will increase dramatically the upcoming decades. Clearly, actions need to be taken on all levels of the national, regional and global economies in order to turn this trend. One of the European Union's approaches to this urgent problem is the promoting of renewable energy, and the union has established an overall binding target of a 20% share of renewable energy sources in the European Union's energy consumption by 2020, including binding targets for each member state.

In the context of renewable energy wind power represents an energy source of increasing interest, and the wind power industry is currently experiencing a strong growth. On the basis of the results achieved in this study offshore wind power has

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[18] A *guaranty of origin* is a certificate that guarantees that electrical power is produced from renewable energy sources.

proved a promising option for electricity production, highly capable of promoting emission reduction in the electricity sector. Even though there are some environmental impacts associated with electricity generation from offshore wind power these impacts are considered imperceptible compared to fossil fuel based electricity[19]. According to the scenario analysis performed in this study, a big Scandinavian investment in offshore wind power could have a considerable influence on the Scandinavian electricity mix, making the EU renewable target an achievable goal for Denmark and Sweden, as well as contributing to other European countries' renewable targets in terms of power export. In order to obtain an economical and environmental sustainable offshore wind power development some factors must however be taken into account. A consideration in terms of nuclear power should be made; of the importance of phasing out nuclear power relative to the importance of reducing greenhouse gases. An optimal solution for the Norwegian power system should be found, enhancing a development towards offshore wind power production. Both the Norwegian energy-intensive industry and the power export must then be taken into consideration. The EU directive is currently badly adapted to the Norwegian energy system, involving regulations that could potentially work as a restrictive factor for the future development of the Norwegian offshore wind industry. According to the results of this study Norway could benefit highly from a future offshore wind industry in terms of increased value added. A solution that promotes Norwegian offshore wind power will according to this be advantageous for both Norway and the EU. With a well developed wind power industry in the Northern countries a flexible electricity system could be developed, which combines wind power and controllable hydro power. In this way the Nordic countries' grid could work as a stabilizer to the European grid, delivering renewable energy to Europe.

By performing this study a wider insight of the complex system of economical and environmental flows constituting the production of offshore wind power was gained. On the per-unit basis the trade patterns, the composition of the wind power economy and the associated emissions distribution were uncovered. The scenario analysis simulated how the economy was responding to an entry of a considerable Scandinavian offshore wind power industry. Compared to a traditional LCA approach the built in characteristics of the MRIO model enabled a more thorough study of the emission value chains and trade patterns of the wind power industry. The inputs and hence the emissions related to a specific output are often dispersed across long value chains, embracing various sectors and regions. This is also the case for offshore wind power. In order to measure the bulk of the environmental impacts caused by wind power generation one must track several production steps down the value chain. By employing and adjusting the MRIO

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[19] Based on emission data from Ecoinvent, GWP [g/kWh generated]: Coal: 952, Natural gas: 595. Petroleum: 695

model to enable study of offshore wind power all background system flows of offshore wind power generation could be included, providing a complete system boundary. The EEIO approach is also suitable when the environmental advantage of wind power production is to be evaluated. Since there is no direct emissions associated with wind power the effect of implementing wind power into the economy is found indirectly by studying the change in the electricity mix. An important question to address here is therefore to what purpose the wind power is used, and what the wind power is replacing; what is the alternative to implementing wind power into the economy? EEIO analysis has uniquely proved to be a capable approach for addressing these types of questions. The EEIO approach enables a more comprehensive study of the emissions associated with trades between countries. Domestic emission data is normally reported by only considering the emissions that occurs physically in the domestic country. However, the emissions associated with the production of the products consumed in the country, i.e. the emissions embodied in import of goods and services are not accounted for in national emission reporting. By applying the MRIO framework and performing an EEIO analysis the total emissions associated with the consumption within a country could be measured. This gives a more accurate value of the environmental impact that a country is responsible for, which in turn could yield increased understanding and hence increased consciousness about the environmental consequences connected to consumption of goods and services.

During this study some new fields of interest have emerged, and these will hereby be addressed and suggested as interesting topics for further study. As argued in the discussion part, ideally speaking the industrial sectors in the industry flow matrix should be scaled according to both energy efficiency rates and projections on the fuel mix used in the industry sectors. A number of projections developed by the PRIMES framework are available, and the effect from adjusting the model according to projections on energy consumption and efficiency rates could be an interesting field in a further study. A prevailing question regarding the future Norwegian wind power industry is whether Norway should export its power high-priced or sell its power low-priced to the domestic industry. From the environmental perspective an interesting field of study could be the outcomes of the two scenarios of power sales, since one of the scenarios involves benefits in terms of high emission efficiency for Norwegian energy-intensive industry, while the other involves environmental advantages in terms of phasing out of fossil fuels.

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Appendix A

Background system data

Table 10: The sectors included in the 23 European countries of the background system

	Sectors - NAMEA
1	Products of agriculture, hunting and related services (01)
2	Products of forestry, logging and related services (02)
3	Fish and other fishing products; services incidental of fishing (05)
4	Coal and lignite; peat (10)
5	Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying (11)
6	Uranium and thorium ores (12)
7	Metal ores (13)
8	Other mining and quarrying products (14)
9	Food products and beverages (15)
10	Tobacco products (16)
11	Textiles (17)
12	Wearing apparel; furs (18)
13	Leather and leather products (19)
14	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)
15	Pulp, paper and paper products (21)
16	Printed matter and recorded media (22)
17	Coke, refined petroleum products and nuclear fuels (23)
18	Chemicals, chemical products and man-made fibres (24)
19	Rubber and plastic products (25)
20	Other non-metallic mineral products (26)
21	Basic metals (27)
22	Fabricated metal products, except machinery and equipment (28)

23	Machinery and equipment n.e.c. (29)
24	Office machinery and computers (30)
25	Electrical machinery and apparatus n.e.c. (31)
26	Radio, television and communication equipment and apparatus (32)
27	Medical, precision and optical instruments, watches and clocks (33)
28	Motor vehicles, trailers and semi-trailers (34)
29	Other transport equipment (35)
30	Furniture; other manufactured goods n.e.c. (36)
31	Secondary raw materials (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, electricity n.e.c.
36	Electricity from hydropower
37	Electricity from wind power
38	Collected and purified water, distribution services of water (41)
39	Construction work (45)
40	Trade, maintenance and repair services of motor vehicles and motorcycles; retail sale of automotive fuel (50)
41	Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)
42	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)
43	Hotel and restaurant services (55)
44	Land transport; transport via pipeline services (60)
45	Water transport services (61)
46	Air transport services (62)
47	Supporting and auxiliary transport services; travel agency services (63)
48	Post and telecommunication services (64)
49	Financial intermediation services, except insurance and pension funding services (65)
50	Insurance and pension funding services, except compulsory social security services (66)
51	Services auxiliary to financial intermediation (67)
52	Real estate services (70)
53	Renting services of machinery and equipment without operator and of personal and household goods (71)
54	Computer and related services (72)
55	Research and development services (73)
56	Other business services (74)
57	Public administration and defence services; compulsory social security services (75)
58	Education services (80)

59	Health and social work services (85)
60	Sewage and refuse disposal services, sanitation and similar services (90)
61	Membership organisation services n.e.c. (91)
62	Recreational, cultural and sporting services (92)
63	Other services (93)
64	Private households with employed persons (95)

Table 11: The sectors included in the eight regions representing "Rest of the World" in the background system

	Sectors - GTAP
1	Paddy rice
2	Wheat
3	Cereal grains nec
4	Vegetables, fruit, nuts
5	Oil seeds
6	Sugar cane, sugar beet
7	Plant-based fibers
8	Crops nec
9	Cattle,sheep,goats,horses
10	Animal products nec
11	Raw milk
12	Wool, silk-worm cocoons
13	Forestry
14	Fishing
15	Coal
16	Oil
17	Gas
18	Minerals nec
19	Meat- cattle,sheep,goats,horse
20	Meat products nec
21	Vegetable oils and fats
22	Dairy products
23	Processed rice
24	Sugar
25	Food products nec
26	Beverages and tobacco products
27	Textiles

28	Wearing apparel
29	Leather products
30	Wood products
31	Paper products, publishing
32	Petroleum, coal products
33	Chemical,rubber,plastic prods
34	Mineral products nec
35	Ferrous metals
36	Metals nec
37	Metal products
38	Motor vehicles and parts
39	Transport equipment nec
40	Electronic equipment
41	Machinery and equipment nec
42	Manufactures nec
43	Electricity from hard coal; gas, steam and hot water from coal
44	Electricity from nuclear power
45	Electricity from natural gas
46	Electricity from petroleum, electricity n.e.c.
47	Electricity from hydropower
48	Electricity from wind power
49	Gas manufacture, distribution
50	Water
51	Construction
52	Trade
53	Transport nec
54	Sea transport
55	Air transport
56	Communication
57	Financial services nec
58	Insurance
59	Business services nec
60	Recreation and other services
61	PubAdmin-Defence-Health-Educat
62	Dwellings

Table 12: The regions of the background system

	Regions
1	Austria
2	Belgium
3	Czech Republic
4	Denmark
5	Estonia
6	Finland
7	France
8	Germany
9	Hungary
10	Ireland
11	Italy
12	Lithuania
13	Luxembourg
14	Malta
15	Netherlands
16	Norway
17	Poland
18	Portugal
19	Slovakia
20	Slovenia
21	Spain
22	Sweden
23	United Kingdom
24	**Oceania**
25	**China**
26	**Asia**
27	**N. America**
28	**S. America**
29	**RO UE**
30	**Middle East**
31	**Africa**

Table 13: The countries included in the eight regions representing “Rest of the World”

	Oceania
1	Australia
2	New Zealand
	Asia
1	India
2	Indonesia
3	Pakistan
4	Bangladesh
5	Russia
6	Japan
	North America
1	USA
2	Mexico
3	Canada
	South America
1	Brazil
2	Colombia
3	Argentina
	Rest of Europe
1	Bulgaria
2	Croatia
3	Cyprus
4	Greece
5	Iceland
6	Latvia
7	Romania
8	Switzerland
	Middle East
1	Turkey
2	Iran
3	Iraq
4	Saudi Arabia
	Africa
1	Nigeria
2	Ethiopia
3	Egypt
4	D. R. Congo
5	South Africa

Table 14: The electricity mixes used for the 31 regions of the background system

	Hard Coal	Nuclear	N Gas.	Petroleum	Hydro	Wind
Austria	7,7 %	-	13,5 %	3,0 %	75,7 %	-
Belgium	16,2 %	60,5 %	20,1 %	1,0 %	2,1 %	-
Czech Republic	22,1 %	54,5 %	12,6 %	1,5 %	9,3 %	-
Denmark	48,8 %	-	25,7 %	13,0 %	0,1 %	12,4 %
Estonia	-	-	92,3 %	6,9 %	0,6 %	-
Finland	15,1 %	39,8 %	17,9 %	1,1 %	26,0 %	-
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 %	-
Ireland	30,8 %	-	41,8 %	21,1 %	5,2 %	1,1 %
Italy	9,8 %	-	38,3 %	32,4 %	19,2 %	0,2 %
Lithuania	-	74,3 %	14,3 %	5,8 %	5,7 %	-
Luxembourg	-	-	20,8 %	-	76,8 %	2,4 %
Malta	-	-	-	100 %	-	-
Netherlands	27,4 %	4,8 %	62,8 %	3,8 %	0,2 %	1,0 %
Norway	0,0 %	-	0,1 %	0,0 %	99,8 %	0,0 %
Poland	92,2 %	-	1,0 %	2,1 %	4,6 %	0,0 %
Portugal	34,7 %	-	17,0 %	20,0 %	27,9 %	0,4 %
Slovakia	11,9 %	58,0 %	11,9 %	0,7 %	17,5 %	-
Slovenia	3,3 %	51,5 %	3,2 %	0,6 %	41,4 %	-
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 %	-	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 %	-	55,8 %	33,7 %	9,9 %	-
Africa	58,5 %	2,9 %	24,0 %	5,1 %	9,3 %	0,2 %

Table 15: The annual electricity demand for the countries included in the analysis.

Country	Annual electricity demand (2000) [TWh]
Denmark	33
Germany	483
Netherlands	98
Norway	110
United Kingdom	329
Sweden	129
Finland	97
Poland	75
EU27	2526

Appendix B

Foreground system data

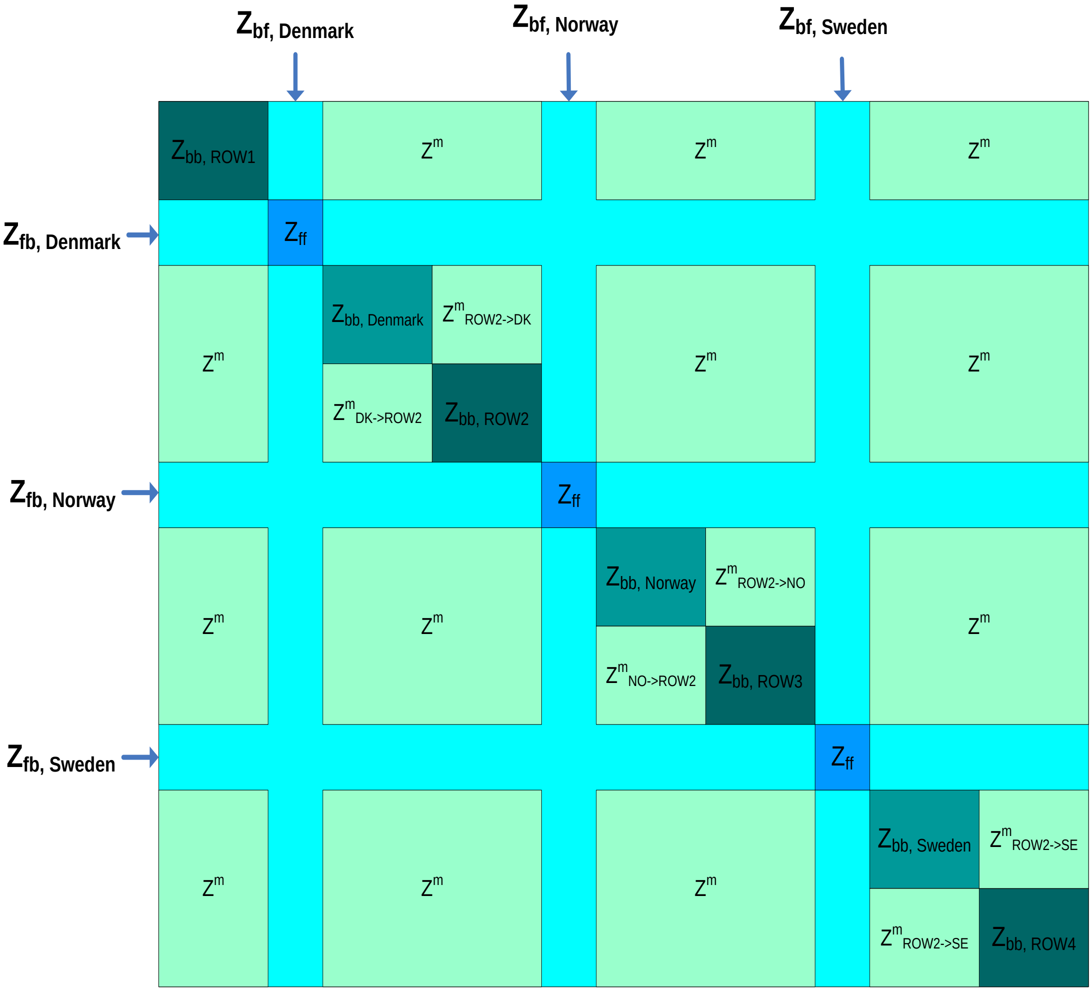

Figure 32: Sketch of the structure of the hybrid system, including all the three foreground systems

Table 16: The foreground system sectors and the NACE sectors that were used as proxies for the different sectors

Foreground system category		Coresponding NACE sector
Steel	27	Manufacture of basic metals
	271	Manufacture of basic iron and steel
Copper, lead and aluminium	27	Manufacture of basic metals
	2720	Manufacture of basic precious and non-ferrous metals
Glass reinforced plastic	26	Manufacture of other non-metallic mineral products
	261	Manufacture of glass and glass products
Rotor	29	Manufacture of machinery and equipment n.e.c.
	291	Manufacture of general purpose machinery
	2911	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines
Nacelle	31	Manufacture of electrical machinery and apparatus n.e.c.
	311	Manufacture of electric motors, generators and transformers
Tower	29	Manufacture of machinery and equipment n.e.c.
	291	Manufacture of general purpose machinery
	2911	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines
Ballast and mooring	26	Manufacture of other non-metallic mineral products
	269	Manufacture of non-metallic mineral products n.e.c.
	2695	Manufacture of articles of concrete, cement and plaster
	2696	Cutting, shaping and finishing of stone
Cable system	31	Manufacture of electrical machinery and apparatus n.e.c.
	313	Manufacture of insulated wire and cable
Substations	31	Manufacture of electrical machinery and apparatus n.e.c.
	311	Manufacture of electric motors, generators and transformers
Installation and dismantling	45	Construction
	451	Site preparation

Wind farm maintenance	40 401	Construction Site preparation
Testing and commissioning	74 742	Other business activities Architectural, engineering and other technical activities
Project management	74 742	Other business activities Architectural, engineering and other technical activities
Land rent, administration, miscellaneous	75 751	Public administration and defence; compulsory social security Administration of the State and the economic and social policy of the community
Power from the grid	40 401	Electricity, gas, steam and hot water supply (in Z: electricity from wind) Production, transmission and distribution of electricity
Insurance	66 6603	Insura*nc*e and pension funding, except compulsory social security Non-life insurance

Table 17: The mathematical structure of the foreground system

	1. Copper [ton]	2. Aluminium [ton]	3. Lead [ton]	4. Steel [ton]	5. Glass fibre [ton]	6. Rotor [p]	7. Nacelle [p]	8. Tower [p]	9. Cable system [p]	10. Substations [p]	11. Ballast and mooring [p]	12. Installation and dismantling [one w.f.]	13. O&M [one w.f., 25 y]	14. Other capital costs [one w.f.]	15. Wind electricity generation [GWh]
1. Copper [ton]	-	-	-	-	-	-	$a_{1,7}$	-	$a_{1,9}$	$a_{1,10}$	-	-	-	-	-
2. Aluminium [ton]	-	-	-	-	-	-	$a_{2,7}$	-	$a_{2,9}$	$a_{2,10}$	-	-	-	-	-
3. Lead [ton]	-	-	-	-	-	-	-	-	$a_{3,9}$	$a_{3,10}$	-	-	-	-	-
4. Steel [ton]	-	-	-	-	-	$a_{4,6}$	$a_{4,7}$	$a_{4,8}$	$a_{4,9}$	$a_{4,10}$	-	-	-	-	-
5. Glass fibre [ton]	-	-	-	-	-	$a_{5,6}$	$a_{5,7}$	-	-	$a_{5,10}$	-	-	-	-	-
6. Rotor [p]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{6,15}$
7. Nacelle [p]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{7,15}$
8. Tower [p]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{8,15}$
9. Cable system [p]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{9,15}$
10. Substations [p]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{10,15}$
11. Ballast and mooring [p]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{11,15}$
12. Installation and dismantling [one w.f.]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{12,15}$
13. O&M [one w.f., 25 y]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{13,15}$
14. Other capital costs [one w.f.]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$a_{14,15}$
15. Electricity generation [GWh]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 18: The EU directive's targets for renewable energy shares of the total energy consumption by 2020

	Present renewable share (2005)	Renewable target (2020)
Belgium	2.2%	13%
Bulgaria	9.4%	16%
Denmark	17.0%	30%
Estonia	18.0%	25%
Finland	28.5%	38%
France	10.3%	23%
Greece	6.9%	18%
Ireland	3.1%	16%
Italy	5.2%	17%
Cyprus	2.9%	13%
Latvia	34.9%	42%
Lithuania	15.0%	23%
Luxembourg	0.9%	11%
Malta	0.0%	10%
the Nederlands	2.4%	14%
Poland	7.2%	15%
Portugal	20.5%	31%
Romania	17.8%	24%
Slovakia	6.7%	14%
Slovenia	16.0%	25%
Spain	8.7%	20%
United Kingdom	1.3%	15%
Sweden	39.8%	49%
Czech Republic	6.1%	13%
Germany	5.8%	18%
Hungary	4.3%	13%
Austria	23.3%	34%

Appendix C

Foreground system inventories

Table 19: Total mass of the wind turbine components.

Component		Total mass [tons]
Rotor	Blade [ton/blade]	17.7
	Rotor, total [ton]	110
Nacelle and drive train [ton]		240
Tower [ton]		300
Foundation/ballast and mooring[20]		1000

Table 20: Material breakdown of each wind turbine component

Share of total weight [%]		Pre-stressed Concrete	Steel	Aluminium	Copper	Glass Reinforced Plastic
Rotor	Hub		100			
	Blades[21]		5			95
Nacelle[22]			80	3-4	14	1
Gearbox			98	1	1	
Generator			65		35	
Frame, machinery and shell			85	9	4	3
Tower		2	98			

---

[20] For this category only cost data has been used, and the component is modeled only using proxy sector from the background system

[21] Rotor blades are ether glass reinforced plastic, wood-epoxy or injection molded plastic with carbon fibers

[22] Assumes nacelle, gearbox and 'frame and machinery' constitute 1/3 of the mass each.

Table 21: Material data provided by Vestas' environmental reports

	Material use/ 5 MW turbine
Estimated turbine capacity [MW]	5
Raw materials and consumables [tonnes]	
Iron/steel*	280
Cast iron*	48
Aluminum*	5.5
Brass	0.1
Copper*	1.1
Cables	4.6
Welding wire	1.1
Powder for powder welding	0.68
Oil products (1,000 liters)	2.1
Prepreg	29
SUM Metals and other raw materials [tonnes]	410
Chemical materials [kg]	
Adhesive and coating products (epoxy and PUR)	5 300
Fiberglass	4 600
Polymer materials	2 900
Mould preparation agents	16
Polyester materials (coat, base and hardener)	950
Paint products (for coating blades)	31
Acetone and thinner	140
Energy and water consumption [MWh]	
Electricity	150
Gas	0.48
Total process energy (MWh)	150
Diesel oil (1 000 liters) 5)	4.3
Water [m^3]	490
Waste and scrap [kg]	
Combustible	23 000
Prepreg	4 300
Landfill	5 500
Paper and cardboard	2 400
Plastic	500
Electronic scrap	28
Scrap metal	59 000
Epoxy waste	690
Polyester waste	37
Isocyanate waste	94

Acetone waste	120
Oil emulsions	2 800
Oil products	240
Waste oil	550
Other types of hazardous waste	66
Sum, total volume of waste [kg]	100 000
Waste water [m^3]	220
Totals [tons]	
Combustible	28.0
Landfill	5.5
Waste for recycling	62.0
Hazardous waste	4.6
Emission to the air	
Organic solvents (kg)	300
Dust (kg)	12.0
CO_2 [tonnes]	35.0

* Data from Table 19and Table 20 is used for these materials

Table 22: Energy and material mix for the cable production

Resource	**Consumption/ton of cable produced**
Energy [kWh]	
Electricity	0.86
Gas, e.g. natural gas	0.16
Total	**1.02**
Metals [kg]	
Copper	330
Aluminum	37.6
Lead (with 0,075% Cd and 0,2 % Sn)	194
- Of which cadmium	14.5
- Of which zinc	38.7
Iron and steel [tonnes]	305
Total metals [tonnes]	**866**
Plastics [kg]	
Polyethene (PE)	174
Polyvinylchloride (PVC)	8.2
Polypropene (PP)	14.7
Total plastics	**197**
Paper	

Impregnation paper	35.5
Oil (cable production)	
Impregnation oil*	38.4
Bitumen	
Destilled bitumen	7.8
Other raw materials	
Tape and other materials	9.4
Chemical products [g]	
EPOXI (Filling of cable ends, etc.)	
Araldite	13.1
Oils (to machines, repairs, etc.)	
Impregnating oil	653
Hydraulic oil / Gear box oil	184
Total oils	837
Solvents (cleaning, laboratory work, etc)	
Total solvents	2 090
Solvent based paintings	9.0
Total solvents [l]	**2 099**
Waste management [kg]	
Cardboard and paper	4.5
Electronics Help	0.3
Oils	9.4
Plastics	4.5
Scrap metal	82.4
Wood	3.7
Total	**104.8**
Total amount	
Landfill and incineration with energy recovery	11.4
Toxic waste	20.7

Table 23: Energy and material use for the transformer stations

	Consumption/ transformer station, 220 MVA
Energy [MWh]	
Electrical energy	8 162
Heat energy	264
Raw materials [kg]	
Water	8 822 000
Wood	7 700

Aluminum in ore	176
Bauxite	6 446
Chromium in ore	4.4
Clay	11.66
Copper in ore	13 486
Crude oil	88 000
Gravel	5.94
Hard coal	122 320
Iron in ore	101 200
Lead in ore	0.396
Lignite	1 452
Limestone	3 608
Manganese in ore	1.452
Natural gas	44 000
Nickel in ore	0.682
Sand	11 880
Uranium in ore	20.02
Waste, during life time [ton]	
Hazardous waste	2.6
Regular waste (incl. Water)	3 784
Total waste	3 787
Materials from technosphere [kg]	
Glass fiber	977
Kraft paper	1 302
Copper wire	343
Copper profile	7 491
Presspan	4 657
Porcelain	1 767
Aluminum	1 573
Paint	83.6
Resin	165
Total material from technosphere	**18 359**
Raw material contents in transformer	157 641
Total weight, assembled transformer	176 000
Waste, end of life [kg]	
Hazardous waste	41 800
Recycled waste	120 560
Landfill waste	13 200
Total waste (incl. Hazardous)	**176 000**

Appendix D

Matlab Codes

```
%Creating the MRIO model with foreground systems

function [A,Y,V,L,s] = hybrid_IO()


%Starting timer
clear
clc
t1 = clock;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% COLLECTING DATA AND DEFINING CONSTANTS

load base_data    %Loading the base matrices Z, Y, S and V_EU

%Excel read
disp('Excel read...')
[tot_cost,tot_cost_2,other_costs,petroleum_use_,sector,A_ff,S_
ff_metal,S_ff_wind_farm,S_ff_12] = hybrid_IO_read();

%Background system constants
ind_EU=64;      %Numbers of industries in the EU-regions
ind_ROW = 62;   %Numbers of industries in ROW
EU = 23;        %Number of EU countries
ROW = 8;        %Number of regions in ROW
VA = 7;         %Number of value added categories
Str = 8;        %Number of stressors

country=[4,16,22]; %Countries to study; 4=Denmark, 16=Norway,
22=Sweden

%Foreground system constants
dim_A_ff = 16;          %Dimension of the foreground system
materials = 5;             %Number of metals in the foreground
system
comp  =  7;                     %Wind  farm  components  in  the
foreground system
CS  =  [6,7,8,9,10,11,13,14,15];   %Cat.  with  stressors  scaled
from S
```

```
material_sector   =   [21,17];   %("metal"   and   "petroleum"
industries)
D = [5,6,7,8,9,10,11];     %Sectors given specific metal use
CC = 4;                          %industries in "other capital
costs"
petroleum_use      =      [zeros(1,materials),petroleum_use_];
%petroleum cost

%Calculations:
dim_b = ind_EU*EU+ind_ROW*ROW;           %dimension   of   old
system
dim_hybrid = dim_b+size(country,2)*dim_A_ff; %Dimension of new
system

%STRESSORS AND VALUE ADDED - Defining the big S and V
V_ROW = zeros(VA,dim_b-EU*ind_EU);
V = [V_EU,V_ROW];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Creating the V_vector
disp('Creating V_vector...')
[V] = hybrid_IO_1(V);


%Calculating x
disp('Calculating x...')
[x] = hybrid_IO_2(Z,Y,V_v);

%Creating the A-matrix
disp('Creating the A-matrix...')
[A] = hybrid_IO_8(x,Z);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Scaling the stressors
disp('Scaling the stressors...')
[s] = hybrid_IO_3(S,x,Z,Y);

%Adding the emissions to S_ff
disp('Adding the emissions to S_ff...')
[S_ff]                                                       =
hybrid_IO_4(Z,tot_cost_2,country,dim_A_ff,s,CS,CC,other_costs,
materials,...
         ind_EU,sector,S_ff_metal,S_ff_wind_farm,S_ff_12);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% FOREGROUND SYSTEM MATRICES

%Getting the A_bf, V_bf and S_ff for the different countries,
unmodified
disp('Getting the A_bf and V_bf for the different countries,
unmodified...')
```

```
[A_red,V_red,S_red]=hybrid_IO_5(A,V_v,country,sector,ind_EU,di
m_A_ff,..
                    other_costs_share_100,s,VA,CC);

%Scaling the A_bf columns according to price data:
disp('%Scaling the Z_bf colums according to price data...')
[A_red,V_red,met]                                              =
hybrid_IO_6(A,A_red,V_red,S_red,petroleum_use,...
country,material_sector,tot_cost,ind_EU,materials,comp,sector)
;

%Adding the known sectors to A_red:
disp('Adding  the  known  sectors,  metal  and  petroleum,  to
A_red...')
[A_red] = hybrid_IO_7(A_red,country,ind_EU,...
          petroleum_use,material_sector,materials,comp,met);

%Creating hybrids:
disp('Creating hybrids...')
[A,S,V,L]                                                      =
hybrid_IO_9(s,Y,x,V_v,ind_EU,A_red,country,A,A_ff,S_ff)  ;

%Creating hybrid Y for all years:
[Y] = scenarios_hybrid_Y() ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Run time
t2 = clock;
sekunder        =        (t2(4)*60*60+t2(5)*60+t2(6))         -
(t1(4)*60*60+t1(5)*60+t1(6));
minutes = floor(sekunder/60);
if minutes==1
    sekunder = sekunder - minutes*60;
    disp(['Run  time:  '  num2str(minutes)  '  minute  and  '
num2str(sekunder) ' seconds.'])
elseif minutes>=2
    sekunder = sekunder - minutes*60;
    disp(['Run  time:  '  num2str(minutes)  '  minutes  and  '
num2str(sekunder) ' seconds.'])
else
    disp(['Run time: ' num2str(sekunder) ' seconds.' ])
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% RUNNING SCENARIOS

%Defining and reading constants
country = [4,16,22]; %Countries to analyze
ind_EU = 64; %Numbers of industries in EU countries
m = 16;     %Foreground system setors

%Excel read
el_price = xlsread('cost.xls','el_prices','B3:X3')';
%reading EL-pricess (31 regions)
M_scenario = xlsread('cost.xls','scenarios','C5:E7');
%Reading increase in offshore wind power
H_scenario = xlsread('cost.xls','scenarios','G5:I7');
%Reading increase in offshore wind power

load Y_2000_2030

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% For the scenario without offshore wind power:
k=1; %for = year (1=2010, 2=2020, 3=2030)

Y=Y_2000_2030(:,1+93*k:93+93*k);

x = sum(Z,2)+sum(Y,2);
x(x==0)=min(x(x>0))*0.1;
A = Z*inv(diag(x));
L=inv(eye(size(A,2))-A);

save Z_Y_2000 Z Y

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% For the scenario with offshore wind power:
load Z_Y_2010

scenario = M_scenario; %could be changed to H_scenario

k=1; %k = year (1=2010, 2=2020, 3=2030)
load Z_Y_2010

[Y,Z] = sell_wind_power(Z,Y,el_price,scenario,k);

save Z_Y_2010_H Z Y

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [Y,Z] = sell_wind_power(Z,Y,el_price,scenario,k)

[Z,Y,rest_EL]=sell_wind_power_DOM(Z,Y,el_price,scenario,k);

[Z,Y]=sell_wind_power_IMP(Z,Y,el_price,rest_EL);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```