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Environmental Assessment of Aluminium Production in Europe

Current Situation and Future Scenarios

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Problem Description

"The objective of this project is to assess the emissions associated with the present European aluminium production and consumption activities and analyze future scenarios for this. The scenarios can include technology change and improvements as well as relocation of production activities. For this purpose a multiregional input-output database shall be adapted and applied."

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Preface

This Master's thesis was written during spring 2009 as the final stage of my MSc degree in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). Chapter 2, as well as sections 4.1 to 4.4, were written in collaboration with four fellow Master students in the Industrial Ecology Programme of the Norwegian University of Science and Technology.

I would like to thank my supervisor at NTNU, associate professor Anders Hammer Strømman, for guidance and advice, as well as the good people of Elkem Aluminium (Alcoa Norway from April 1, 2009), especially my co-advisor Ronny Vatland, for supporting me along the way. I would also like to express my gratitude to my fellow students at the Industrial Ecology Programme — especially my office-mates in the LCA laboratory, Børge, Stian, Thomas and Åsa, with whom I spent so many late nights working on this thesis.

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Abstract

A multiregional input-output model representing the world in the year 2000 was constructed based on statistical data, and combined with process specific data on a primary aluminium supply chain, to create a model of the global primary aluminium industry. Using input-output methodology, total emissions of eight substances due to primary aluminium production, their size and origins, were estimated and expressed in terms of global warming potential (GWP) and acidification potential (AP). Simulations from 2000 to 2030 were run based on final demand estimates from external GDP projections and three assumed development scenarios. The baseline, scenario 0, assumed no changes in technologies or relative production and trade patterns – only the model's response to the expected change in final demand was analyzed. By contrast, both scenarios 1 and 2 assumed that the additional aluminium production predicted by the baseline would be produced exclusively in China. Scenario 2 employed the added assumption that the Norwegian aluminium production would experience a steady decline from its 2000 level to zero by 2030.

The baseline scenario showed rapidly increasing aluminium output towards 2030, following the expected GDP developments. Emissions followed the same trend, increasing about 3.3 times over the three decades. As for total *cradle-to-gate* impacts of primary aluminium production, the model showed large variations from one region to another. Emissions per ton of Chinese primary aluminium were high relative to most other regions, hence the total global GWP and AP from primary aluminium production rose more rapidly in scenarios 1 and 2 than in scenario 0. By 2030, the GWP in scenarios 1 and 2 were 11.4% and 12.5% higher than in the baseline, while AP were 50.0% and 51.9% higher.

Samandrag

Ein multi-regional kryssløpsanalysemodell som representerte verda i år 2000 vart konstruert basert på statistiske data, og kombinert med prosesspesifikk informasjon om ei produksjonskjede for primæraluminium for å oppnå ein modell av den globale aluminiumsindustrien. Ved å nytta input-output-metodar vart totale utslepp grunna produksjon av primæraluminium, både når det gjaldt storleik og opphav, estimerte for åtte kjemiske substansar, og uttrykt som globalt oppvarmingspotensiale (GWP) og forsuringspotensiale (AP). Simuleringar frå 2000 til 2030 vart utførte basert på utviklingsestimat for etterspurnad ("final demand") frå eksterne vurderingar av framtidige endringar i bruttonasjonalprodukt (BNP), og tre ulike utviklingsscenarier. Scenario 0, som representerte "grunnlina", gjekk ut frå at teknologi og relative produksjons- og handelsmønster ville vera uendra, slik at ein fekk analysert modellen sin respons på den forventa endringa i etterspurnad. Både scenario 1 og scenario 2 var derimot basert på hypotesa om at all ny produksjon av aluminium oppretta etter år 2000 skulle gå føre seg i Kina. Scenario 2 gjekk i tillegg ut frå at den norske aluminiumsindustrien ville bli fasa ut gradvis over perioden, frå nivået det låg på i 2000 ned til null produksjon i 2030.

Grunnscenarioet synte rask vekst i aluminiumsproduksjon from mot 2030, i takt med den venta auken i BNP. Utsleppa følgde same trend, og auka omtrent 3,3 gonger over dei tre tiåra. Når det gjaldt totale spesifikke *vugge-til-port*-miljøkonsekvensar frå produksjon av primæraluminium, synte modellen store variasjonar frå region til region. Utslepp per tonn kinesisk primæraluminium var høgare enn dei fleste andre regionar, slik at total global GWP og AP grunna aluminiumsproduksjon auka raskare i scenario 1 og 2 enn i scenario 0. I 2030 var utrekna GWP i scenario 1 11.4% høgare, og i scenario 2 12.5% høgare, enn dei var for scenario 0, medan tilsvarande auke i AP var 50.0% og 51.9% relativt til scenario 0.

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Some applied abbreviations and acronyms

AP	Acidification potential
CO_2-eq	Carbon dioxide equivalents
EEA	European Aluminium Association
EEC	Emissions embodied in consumption
EEIOA	Environmentally extended input-output analysis
EET	Emissions embodied in trade
ESA	European System of Accounts
EU23	The 23 (European) foreground regions modeled here
EUR	Europe
GDP	Gross Domestic Product
GHG	Greenhouse gases
GTAP	Global Trade Analysis Project
GWP	Global warming potential
IAI	International Aluminium Institute
IEA	International Energy Agency
IOA	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
MRIO	Multi-regional input-output
NACE	Nomenclature des Activités Economiques dans la Communauté Européenne
NAMEA	National accounting matrices with environmental accounts
nec	Not elsewhere classified
NMVOC	Non-methane volatile organic compounds
NOK	Norwegian kroner
NO_x	Nitrous oxides
PFC	Perfluorocarbons
ROW	Rest of the world
SIOT	Symmetric input-output tables
SNA	System of national accounts
SUT	Supply and use tables
SO_2-eq	Sulfur dioxide equivalents
SO_x	Sulfur oxides
USGS	U.S. Geological Survey

Table 1: List of Abbreviations

Chapter 1

Introduction

The global economy has been in a continuous state of growth since the Second World War. Although it is currently suffering from the last months of economic recession, this will most likely not last — and on the global scale we will probably not see any decline in output, so much as a decline in output *growth*. The IMF (2009) currently estimates a global GDP growth in 2009 of 0.5%, rising back to 3.0% as early as 2010.

The global industrial output is closely related to economic growth. Consequently, it has been hit hard by the recession — nevertheless the general trend over the past few decades has been rapid growth. This is especially true for the aluminium industry and the primary metals industry as a whole. Aluminium is employed in areas from transportation and construction to packaging and electronics, and as the large economies of Asia have been experiencing staggering growths over the past years, demands have gone through the roof. According to the U.S. Geological Survey (USGS), the global aluminium output increased by an astounding 80% from 1998 to 2008 (USGS, 2009). Of metals, only steel is currently produced in larger quantities — and its lead is shrinking.

To meet this increased demand, primary aluminium producers all over the world are looking into possibilities of expanding their production. New production facilities are being constructed, and current facilities are being upgraded. When the decision is made to invest in new production capacity, a key decision is where to locate the production, and a number of factors determine the best choice. Favourable electricity prices are critical, due to the electricity intensive nature of the production process. In the primary metals industry, the high density of the products encourages producers to locate production close to the consumers to reduce transportation costs.

There is, however, another factor in play that could draw producers from Asian countries with inexpensive production. Concerns about CO_2 emissions and potential global warming has emerged as one of the primary focus areas for governments and consumers, and consequently also for industries. Governments worldwide are tightening emission caps and committing themselves to increasingly dramatic emission reduction schemes for the coming decades, and as a global carbon emission trade system emerges, there will be strong incentives for aluminium producers to locate their production to regions with cleaner electricity production. This is reinforced by a trend of increasing consumer concerns of the origins of products and their environmental “footprint”, that is the total environmental consequences of its production.

Input-output analysis is a powerful tool to analyze the large-scale flows of products and services in an economy. By adding information on emission intensities to the input-output tables, this tool can be used to model global emissions, identify their sources and track the final demands that generate them. Such environmentally extended multiregional input-output analyses can shed light on the emissions embodied in production, trade and consumption — information that will be crucial for an emerging global initiative to curb anthropogenic emissions.

1.1 Background

In 2002 the Kyoto protocol was ratified by all the countries that were at that time EU members. The EU is committed to reduce their greenhouse gas emissions by 8% relative to the base year 1990 by 2008–2012, and by 20% by 2020. According to the European Environment Agency, the EU-27 countries have reduced their emissions significantly since 1990, but current projections suggest that they will not reach the goal for 2020 (EEA, 2008).

1.2 Previous work

The academic disciplines of input-output analysis and life cycle assessment are fairly young. As such, life cycle inventory (process flow) data are often scarcely reported and hard to come by, and only a limited amount of these studies exist. Few deal with primary aluminium production; however the data material is improving, mainly due to efforts by the industry itself. The International Aluminium Institute (IAI) and the European Aluminium Association (EAA) both have collected such data from their members, and presented average life cycle inventories for aluminium producers (IAI, 2007b; EAA, 2008), so as to enable researchers to perform such analyses based on a common, representative data framework. These were the inventories used when modeling the foreground sectors here.

Steen-Olsen (2008) performed a process-based life cycle assessment of Norwegian primary aluminium production, based on Elkem Aluminium's (now: Alcoa Norway's) smelter at Lista, Norway. This study found total *cradle-to-gate* global warming potential (GWP) and acidification potential (AP) of 8.92 tons CO_2-eq and 46.2 kg SO_2-eq per ton primary aluminium, respectively. The study suggested that the energy source used for electricity production was the single most important factor contributing to these impacts for most regions, with Norway being a special case due to its large supply of hydro power. Indeed, when the smelter was hypothetically relocated to Germany, the GWP increased more than two and a half times.

Bergsdal *et al.* (2004) also did a study of environmental impacts from primary aluminium production, based on IAI inventories. They report total greenhouse gas (GHG) emissions of 12.7 tons CO_2-eq per ton primary aluminium, 83% of which originate from the plant itself. Electricity production accounts for 46% of the total CO_2 emissions. Corresponding results for an Australian primary supply chain were found by Tan and Khoo (2005) to be 18.3 tons CO_2-eq and 90.6 kg SO_2-eq per ton primary aluminium. This study assumed that all the direct electricity requirements were supplied by a coal-fired power plant. According to their report, nearly 85% of the GWP found in their study originated from the power plant.

Norgate *et al.* (2007) compared life cycle GWP and AP for several metals, including aluminium. They report a total GWP of 22.4 tons CO_2-eq and 131 kg SO_2-eq per ton primary aluminium. They assume an electricity mix corresponding to a global average which they report were 36% coal-based and 49% hydro power based.

1.3 Objectives

This study aims to to model the origins of global emissions associated with the aluminium industry, with a special focus on Europe, for the year 2000. By incorporating specific data for the aluminium sector into a multiregional input-output database, inputs to and outputs from the aluminium sector will be studied, and the emissions linked to these flows will be analyzed. By using the input-output framework, emissions can be studied from various perspectives — such as direct emissions from the aluminium sector, total emissions in other sectors due to the production of primary aluminium, emissions embodied in trade and end-use of aluminium based products and so on.

The study will also employ gross domestic product (GDP) projections to build future scenarios up to 2030. By gradually scaling the global final demand of goods and services according to GDP projections and imposing this on the model, resulting flows and emissions will be modeled and studied. As alternatives to this *baseline* scenario, one or more alternative scenarios will be modeled, in which certain key parameters will be changed relative to the baseline scenario. The direct and indirect effects throughout the global economy of such an assumption will be studied and compared to the baseline scenario. The scenarios will be analyzed and compared on an environmental basis in order to be able to draw conclusions on total environmental effects resulting from the assumed change.

1.4 Strategy and report structure

In the next chapter, the concept of input-output analysis and its methodological framework is laid out. This chapter also explains the theoretical foundation used to hybridize input-output models with life cycle data. Chapter 3 provides a broad overview of the process of producing primary aluminium as it is today, and defines the three development scenarios that were assumed in this study. In chapter 4, the process of building the model is explained in detail. Next, chapter 5 presents and analyzes the main results obtained from the model simulations of the three scenarios. Finally, the results are discussed and evaluated in chapter 6. This chapter also contains a conclusion and some suggestions for improvements and future work.

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 analysis (EEIOA). While the first method is generally accepted as one of the best tools for a wide range of processes and products, the latter is considered as more comprehensive, including, *inter alia*, a "systematically complete system boundary" (Crawford, 2007). A proper combination (*hybridization*) of both methods leads to a framework where each method's weaknesses are covered by the other's strengths. In this chapter, the emphasis has been put on input-output, which actually shares its main principles with LCA.

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, a 1973 Nobel Prize laureate, 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). Researchers quickly realized the potential of this framework when 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 40×40 up to 500×500 for the most disaggregated tables. These tables usually show the flows between industrial sectors at *basic* prices: neither trade margins nor taxes and subsidies are taken into account to quantify trade flows.

2.2 Formal framework

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

2.2.1 Basics

Technically speaking, the core of 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 profile of an economy. This matrix has as many inputs as outputs, in a product-by-product matrix each element a_{ij} in this matrix gives the amount of monetary input from sector i 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 € (or $, NOK,...) are necessary to generate 1 € worth 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 demand itself plus the additional internal production required to deliver this final demand:

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

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

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

Another important matrix can be derived: Z, the inter-industry flow matrix, which shows the total flows between any couple of sectors cumulated over one year (generally). It is calculated as follows:

$$Z = A\hat{X} = A\widehat{LY} = A\widehat{(I-A)^{-1}Y} \tag{2.3}$$

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:

$$A = Z\hat{X}^{-1} \tag{2.4}$$

2.2.2 Constructing symmetric A matrices

A challenge arises when it comes to constructing 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 this is generally not the case in reality. In an SIOT, the total product output (q) is distinguished from industry output (g). 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 consume) matrices. Three additional matrices can immediately be derived from this basic set (^{t} denotes a transposing operation):

- The use coefficient matrix

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

- The market share matrix

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

- The product mix matrix

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

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

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

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 is called an "industry technology assumption". Basically, industry i will fabricate all the products it is supposed to supply *exactly in the same way*, same hypothesis for industry j, even though it can produce the same commodities as i. Under this assumption, we must use the following equation:

$$A_{IT,nn} = DB \tag{2.5}$$

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 determine the intermediate product requirements per unit of each product. The expression used here is the following:

$$A_{IT,mm} = BD \tag{2.6}$$

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 applying the so-called "commodity technology assumption". The expression hereafter will be used:

$$A_{CT,nn} = C^{-1}B \tag{2.7}$$

Where B is still the same and C is 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:

$$A_{CT,mm} = BC^{-1} \tag{2.8}$$

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 assuming domestic technology. This however leads to great errors if trade regions have diverging technology (Peters & Hertwich, 2006). Another issue which is not resolved by one-region models is the fact that imports and exports in a region or country are satisfying either intermediate or final demand in the recipient region (Peters, 2007). The total economic output (x) in a region is calculated from the sum of intermediate (A) and net final demand (y), as described in equation 2.2. The net final demand consists of the sum of domestic final demand of domestic produced products (y^d) and final demand of exported products (y^{ex}), minus imported products used in final demand (m):

$$y = y^d + y^{ex} - m \tag{2.9}$$

The industry requirements matrix also includes imports, which are denoted A^{im}. The remaining part of A is the domestic requirements matrix 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 2.9 then becomes:

$$x = (A^d + A^{im})x + y^d + y^{ex} + y^{im} - m \tag{2.10}$$

and the import balance must be maintained,

$$m = A^{im}x + y^{im} \tag{2.11}$$

giving:

$$x = A^d x + y^d + y^{ex} \tag{2.12}$$

which is the domestic activity of a given region. In order to include other activities than domestic, by not assuming domestic technology, a multiregion framework can be useful. The multiregion 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 & 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. As an example, a Norwegian lumber company's demand of Swedish furniture could induce a demand of Norwegian wood to Sweden.

The MRIO framework extends the IOA model, giving a new system consisting of multiple regions. An n-region system with focus on domestic region $i = 1$ will then be (Peters & Hertwich, 2006):

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2n} \\ A_{31} & A_{32} & A_{33} & \dots & A_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & A_{n3} & \dots & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{n1} \end{pmatrix} \tag{2.13}$$

The model will change accordingly for other values of i. The domestic industry demand matrices constitute the diagonals in the A-matrix, while imports and exports make up the rest. 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 scarce. Still, there are two major ongoing projects on developing MRIO datasets. The first one is the Global Trade Analysis Project (GTAP) which has recently released version 7 of its MRIO model (GTAP, undated). This includes 113 regions with 57 sectors. Another MRIO project is EXIOPOL which will be a global multiregional environmentally extended input-output database. The work is supported by the EU 6th framework, leading naturally to that the framework is having higher detail on EU-27. EXIOPOL aims to cover around 130 sectors and products (Tukker *et al.*, 2008).

2.4 Environmental extensions

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

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

$$e = Sx = s(I - A)^{-1}y \tag{2.14}$$

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 contribution to each environmental impact, relative to some reference compound, so that the e vector is converted into total impacts in terms of emission equivalents of the reference compound. The vector of total impacts d, then, is calculated as follows:

$$d = Ce = CSx = CS(I - A)^{-1}y \tag{2.15}$$

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

$$E = \hat{S}x, \tag{2.16}$$

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

$$E^{f.d.} = \hat{s}L\hat{y}, \tag{2.17}$$

where an element $E_{ij}^{f.d.}$ 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:

$$d_n = CSA^ny \tag{2.18}$$

and the cumulative impact after n tiers:

$$d_{n,acc} = CS\sum_{i=0}^{n} A^iy \tag{2.19}$$

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

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 2.14 above, we can extract parts of A and y to determine the EET from region r to region s:

$$EET_{rs} = s_r(I - A_{rr})^{-1}e_{rs} \tag{2.20}$$

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

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

$$EEC_r = s(I - A)y_r^{EEC} \tag{2.21}$$

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

2.5 Environmentally extended input-output life cycle assessment (EEIO-LCA)

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

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

LCA able to analyse the environmental burdens associated with one specific product.

2.5.1 Approach 1: Approximating the product by its sector

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

2.5.2 Approach 2: Product as a new hypothetical industry sector

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

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

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

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

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

$$E = S * X = S * (I - A)^{-1} * Y = S * L * Y \tag{2.22}$$

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

$$Y = \begin{pmatrix} 0 & \dots & 0 & y_{n+1} \end{pmatrix} \tag{2.23}$$

2.5.3 Approach 3: Disaggregating an existing industry sector

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

$$A_{n,j}^{orig} = A_{n,j}^{adj} + A_{n+1,j}^{adj} \tag{2.24}$$

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

$$A_{n,n}^{orig} = (1-k) * (A_{n,n}^{adj} + A_{n+1,n}^{adj}) + k * (A_{n,n+1}^{adj} + A_{n+1,n+1}^{adj}) \tag{2.25}$$

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

$$S_n^{orig} = (1-k) * S_n^{adj} + k * S_{n+1}^{adj} \tag{2.26}$$

Chapter 3

Present and Future Production of Primary Aluminium

3.1 Primary aluminium production

The popularity of aluminium has grown vastly over the last decades as new ways to use it has been recognized. Aluminium has a wide range of favourable properties — it is lightweight, yet strong, it is a good conductor of electricity as well as heat, and it can easily be shaped. On top of this, it can be recycled almost indefinitely while maintaining its quality, in a process that requires only about 5% the energy required to produce primary aluminium (IAI, 2009).

3.1.1 History

As metals go, aluminium has not been around for very long. The reason for this is by no means its scarcity, in fact the soil around us is full of it: about 7.3% of the crust of the earth consists of aluminium compounds (Bergsdal *et al.*, 2004). Out of elements, only oxygen and silicon are more common. Rather, the problem is to produce it. Elemental aluminium is highly chemically reactive, and as such it is never found in its pure form in nature as it will invariably react with other elements to form different kinds of minerals.

Only as late as 1825 was a Danish chemist, H. C. Ørsted of Copenhagen, able to produce pure aluminium from an aluminium-bearing mineral. In the following decades, aluminium was so rare that in fact the French emperor Napoleon Bonaparte is said to have been dining from aluminium plates and cutlery, while his guests had to settle for "common" silverware. In 1886, the real breakthrough came, as the Hall-Héroult electrolytic process of producing aluminium was discovered, the same process that is used today. The process bears its name from its two inventors, C. M. Hall of Ohio, USA and P. L. T. Héroult of Paris, France, who independently of one another discovered it more or less simultaneously.

3.1.2 Process overview

The process of producing primary aluminium is principally the same for virtually all aluminium produced in the world today. In rough terms, it consists of three steps: Mining the bauxite ore, refining it into aluminium oxide (Al_2O_3), and finally separating the pure aluminium from the oxygen in the electrolysis step. A brief walkthrough of the steps is provided below, and figure 3.1 attempts to visualize the process chain with its most important inputs and outputs.

Bauxite mining

Aluminium appears in oxidized form in several common minerals. The source of most of the primary aluminium produced today is *bauxite*, an aluminium rich ore that is found in large quantities in a wide belt along the equator (Thundal, 1991). It is extracted from quarries, typically five to ten meters deep. Consequently, bauxite mining affects relatively large surface areas, posing a potential environmental threat regarding terrestrial ecosystems. Many bauxite mines today have systems in place to restore exhausted mining areas to their original states with only moderate loss of biodiversity.

Bauxite is not a specific mineral, but the name of a group of aluminium rich ores used for aluminium production. The forms of bauxite used are gibbsite ($Al(OH)_3$), böhmite (γ-$AlO(OH)$) and diaspore (α-$AlO(OH)$). Bauxite ores contain roughly 50% aluminium oxides, which in turn is about 50% aluminium. As a rule of thumb, then, 4 tons of bauxite is needed to make 2 tons of aluminium oxide and subsequently 1 ton of aluminium.

Alumina refining

At the alumina refinery, which is commonly located close to the bauxite mine, the bauxite is refined into aluminium oxide. Aluminium oxide, commonly known as *alumina*, is the raw material used in aluminium smelters around the world. The method from which it is extracted from bauxite is named the *Bayer* process after K. J. Bayer, who first invented it.

In the Bayer process, bauxite ore is ground into small pieces and washed, before entering the *digestion* step, in which it is dissolved in sodium hydroxide at elevated temperature and pressure conditions. Insoluble oxide impurities

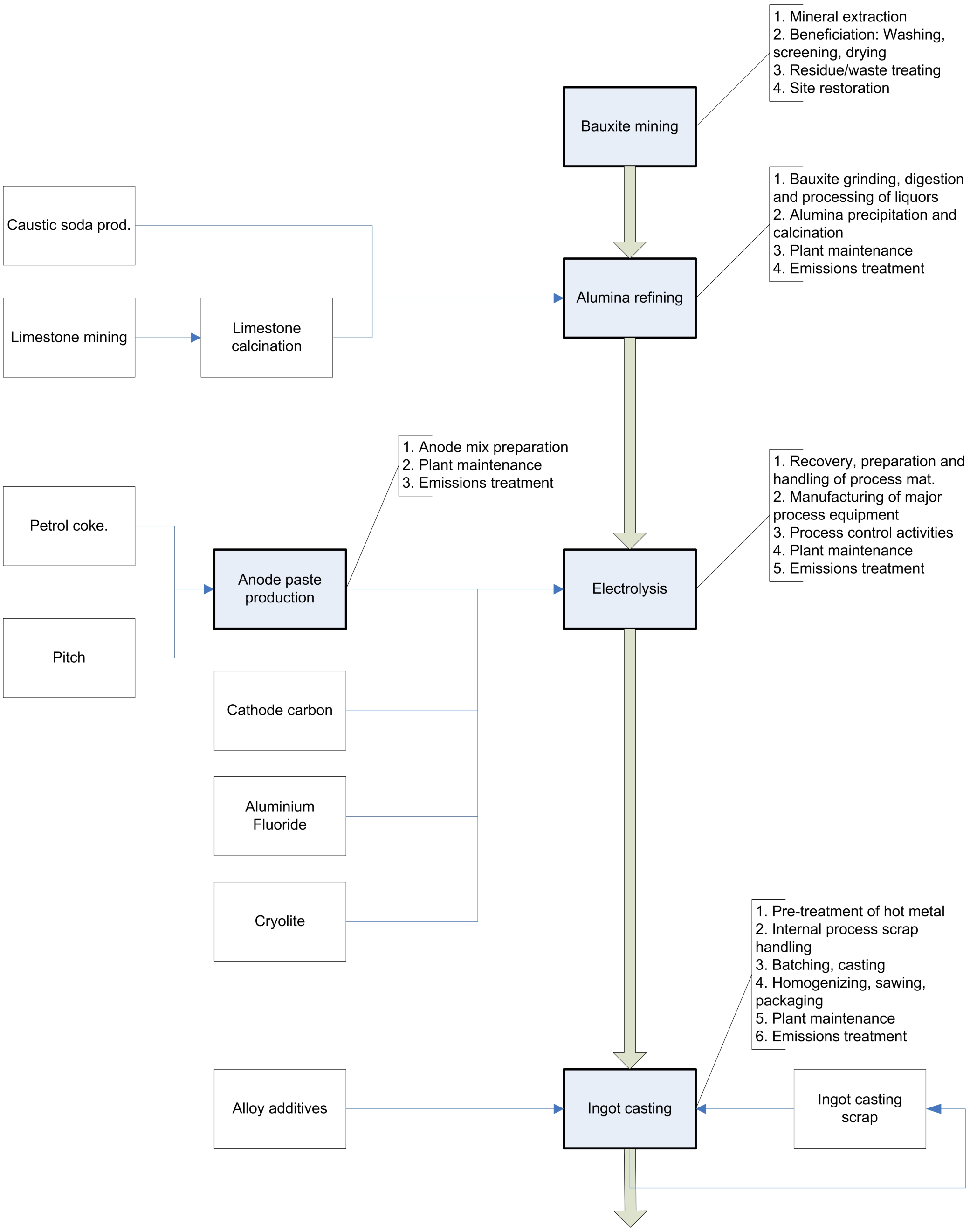

Figure 3.1: Generalized flowchart of primary aluminium production, showing the most important processes, inputs and outputs. Adapted from Steen-Olsen (2008).

sink to the bottom of the solution, whence they are removed. The next step is the *precipitation* step, where aluminium trihydroxide (gibbsite) is extracted by precipitation. The gibbsite is converted to alumina in the *calcination* step at temperatures around 1250°C (Grjotheim & Kvande, 1993). Figure 3.2 shows the process schematically. The chemical reactions taking place in each step are as follows (IAI, 2009):

1. **Digestion**[1]:

$$Al(OH)_3 + Na^+ + OH^- \rightarrow Al(OH)_4^- + Na^+ \quad (3.1)$$

$$AlO(OH) + Na^+ + OH^- + H_2O \rightarrow Al(OH)_4^- + Na^+ \quad (3.2)$$

2. **Precipitation**:

$$Al(OH)_4^- + Na^+ \rightarrow Al(OH)_3 + Na^+ + OH^- \quad (3.3)$$

3. **Calcination**:

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O \quad (3.4)$$

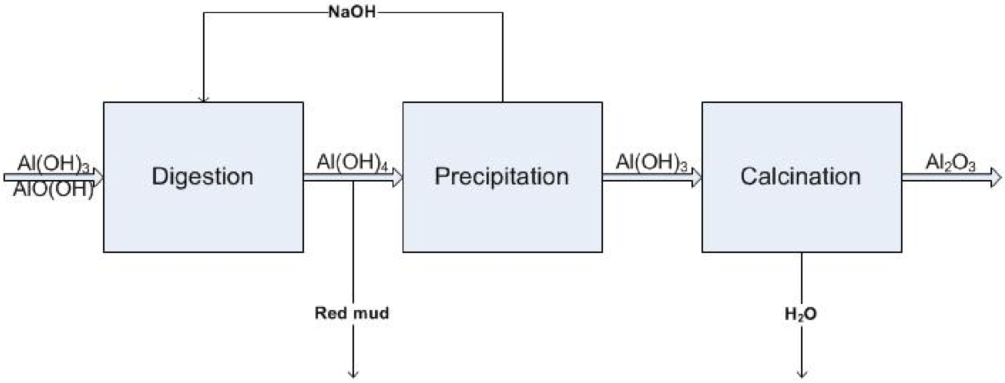

Figure 3.2: Generalized flowchart of the Bayer process, in which aluminium oxide is produced from bauxite ore.

The bauxite residue from the alumina refining is called "red mud" because of its characteristic colour. As only about half the bauxite is alumina, roughly as much red mud is produced as a by-product for every ton of produced alumina (Bergsdal *et al.*, 2004). Tan and Khoo (2005) even estimate

[1]Gibbsite (eq. 3.1) and böhmite/diaspore (eq. 3.2)

this to be more than two tons of red mud for every ton of alumina. The red mud is commonly stored in large landfills, and later recultivated. It is both chemically stable and non-toxic, but sodium hydroxide residue from the digestion step makes it highly alkaline (Bergsdal *et al.*, 2004), which could pose an environmental challenge. Possible ways of using the red mud are currently being investigated.

Aluminium smelting

The Hall-Héroult process is the method used for all large-scale aluminium production today (Norgate *et al.*, 2007). An aluminium plant commonly consists of three main units; an anode factory that supplies the electrolysers in the electrolysis halls with anodes, and a casting house where liquid aluminium from the electrolysers is alloyed and cast into ingots.

The electrolysis halls are the cores of the plant, containing multiple aluminium-producing electrolytic cells (or “pots”). Typically, these cells are lined up in long rows (known as “potlines”), with all the cells in a potline electrically series connected to each other. The (relatively small) plant at Lista, for instance, has three potlines, each with ninety cells. The voltage drop across each cell is modest, only about 4.5 V, but the current is very high, typically 200-350 kA (IAI, 2009). Each cell contains an electrolytic bath which enables the electrolytic process to take place. This bath is mostly molten cryolite (Na_3AlF_6), but also components such as aluminium fluoride (AlF_3) and calcium fluoride (CaF_2), which among other things helps to decrease the required bath temperature from the melting point of alumina at 2060°C to about 960°C (Thundal, 1991; Thonstad *et al.*, 2001).

The cells are large steel cases, which apart from containing the electrolytic bath also act as the cathodes in the electrolysis. On the inside, the cells are lined with thermal insulators and carbon, to protect the cases from the heat and the chemical aggressiveness of the bath. The anodes are overhanging carbon rods that are submerged in the bath.

The electrolytic reaction in which pure aluminium is produced from alumina in the Hall-Héroult process is chemically as follows:

$$\frac{1}{2}Al_2O_3(\text{dissolved}) + \frac{3}{4}C(\text{s}) \longrightarrow Al(\text{s}) + \frac{3}{4}CO_2(\text{g}) \tag{3.5}$$

From the reaction, it is evident that carbon from the anodes will be consumed in the process of extracting pure aluminium from the alumina. The stoichiometric minimum consumption is 3 carbon atoms for every 4 aluminium atoms produced. The product of the reaction, apart from aluminium, is carbon dioxide, which is formed when the consumed carbon react with the oxygen from the alumina. As such at least 1.22 tons of CO_2 is inevitably created per ton of aluminium produced at the electrolysis step.

As the anodes are being consumed, they must be replaced continuously — this is the reason why all aluminium plants contain an anode production facility. The anodes used are produced from petroleum coke to which pitch is added as a binder. The two compounds are mixed and heated so that they can be "baked" together into a solid anode. Two main technologies for producing these anodes are being used today:

- **Söderberg**: In cells that are based on the Söderberg technology, briquettes of coke and pitch are continuously supplied on top of the existing anodes as they are consumed. The anodes are held in metal casings, and as they are consumed, they move downwards into the bath so that the tip of the anode is at a fixed distance from the cathode. As the pebbles move towards the bath, the temperature increases, gradually softening and mixing the coke and the pitch. By the time they reach the bath, the anode mass is baked to a proper anode. The Söderberg technology is the one used at Lista, but it is becoming less and less common.

- **Prebake**: Prebake smelters dominate the global aluminium industry, and today almost all new smelters use this technology (EAA, 2008). As the name suggests, prebake plants make complete, baked anodes at the anode production facility. When an anode is nearly consumed, it is removed and a new one is fitted instead.

The main advantage of the Söderberg technology compared to the prebake technology is the fact that the anodes are more easily produced, as they do not have to be shaped and baked in the anode factory (which would also require more process heat). Also, one avoids the production halts connected to anode replacements — a process that is also potentially risky for workers. The downside, however, is higher electricity consumption and emissions (Bergsdal *et al.*, 2004). As the anode in a Söderberg plant is "provisionally" baked in the cell itself, it is (marginally) flawed compared to the carefully shaped prebake anodes, an important difference when the anode is introduced to the complex chemical environment of the electrolytic bath in the cells.

Liquid aluminium is formed at the bottom of the cell, which acts as the cathode in the electrolysis[2]. Due to its relatively high density, the aluminium

[2] Technically, the cathode is actually the surface of the aluminium melt at the bottom of the cell (Thonstad *et al.*, 2001).

accumulates at the bottom of the bath, enabling it to be siphoned out and sent to the casting house. In the casting house, liquid aluminium from the electrolysis step is mixed with alloying elements and cast into ingots. Common alloying elements are silicon, magnesium and manganese. By alloying the pure aluminium, its structural strength can be significantly increased.

Many primary aluminium plants, among them the Lista plant, buy new scrap aluminium externally and mix with the liquid aluminium at the casting step. This requires a significant input of process heat in order to melt the extra, cold metal, leading to increased emissions from the plant as a whole.

3.2 Scenario modeling

3.2.1 Scenario 0: The baseline scenario

The basis on which the future projections in this study are founded, is the publication entitled "European Energy and Transport: Trends to 2030 — Update 2007", prepared by the Institute of Communication and Computer Systems of the National Technical University of Athens for the European Commission's Directorate-General for Energy and Transport (European Commission, 2008). It employs the PRIMES Energy System Model to simulate growth in gross domestic products for European countries (Capros, 1999).

On average, an annual increase in GDP of at least 2.5% is expected. At a rate like this, the GDP for a country will double in less than three decades. The growth is, however, not predicted to be uniform. Figure 3.3 shows the assumed relative growth for some of the European countries. While Germany is assumed to have a steady, modest growth of around 1.5% annually for the next few decades, some former East bloc countries are expected to experience formidable growths in the years to come. The Baltic countries, represented in figure 3.3 by Estonia and Lithuania, are striking examples. As the graph shows, they can be expected to quadruple their GDP by 2030 according to these projections.

In the model constructed for the present analysis, the final demand will be scaled according to the GDP projections for each European region, where a relative annual change is assumed for each decade and region up to 2030. To decrease the required computational labour, new final demand matrices will be calculated only every tenth year — that is for 2010, 2020 and 2030. In each interval, the most recent final demand matrix will be used as a basis, and scaled using the annual GDP change found in European Commission (2008).

For each of the three future years in study, the following computational

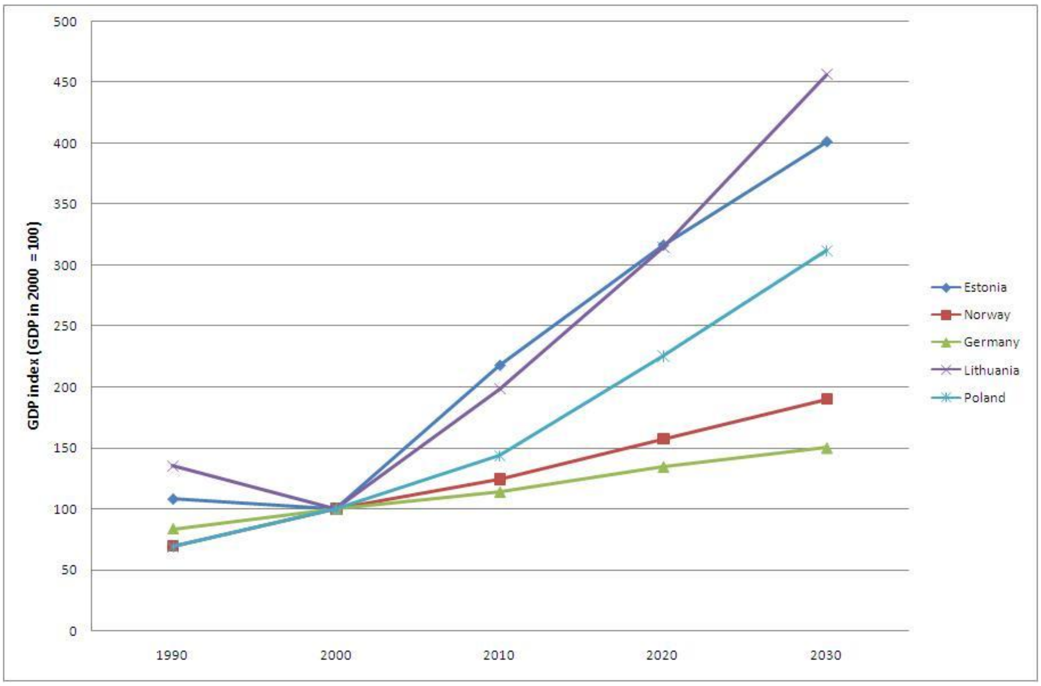

Figure 3.3: Expected relative GDP growth for a selected few European countries

steps will be performed to model a new set of input-output tables based on the estimated final demand for that year — that is, for year n:

1. Based on the estimated new final demand y_n, a vector of resulting total output, x_n, can be created by imposing it on the original technology coefficient matrix A, under the assumption that all sectors keep their original input-output structure. In mathematical terms, this becomes (cf. equation 2.2):
$$x_n = (I - A)^{-1} y_n \tag{3.6}$$

2. By going back from this output vector, the corresponding new flow matrix for the relevant year can be found using the coefficient matrix once again (cf. equation 2.3):
$$Z_n = A\hat{x}_n \tag{3.7}$$

3. As soon as the new flow matrix is calculated, corresponding emissions matrices can be found using the equations outlined in section 2.4.

As the baseline scenario only assumes changes in final demand, its likelihood *as such* is not very high. The intention of this study is to illustrate global economical and environmental repercussions in a hypothetical scenario where only a few certain parameters are changed, while all others are kept constant. As such, one should not regard the scenarios in this study as forecasts, so much as future simulations in a controlled environment. Therefore, technologies are assumed constant, as are prices, trade patterns, energy mixes and specific emissions.

3.2.2 Scenario 1: Chinese expansion

The alternative to the baseline scenario chosen for this study is a simulation of the upcoming few decades where the global aluminium production undergoes dramatic changes relative to the stable baseline scenario. In this scenario, all new aluminium production is assumed to be located in China, while the aluminium outputs of all other regions remain stable at 2000 levels. Otherwise, the assumptions made in scenario 1 are identical to those in the baseline scenario.

Methodologically, the future projections using the assumptions of scenario 1 will be calculated using the same steps described for the baseline scenario. For each future year, however, the new economical transaction matrix Z_n must be manipulated in order to fit the assumptions of this scenario, by ensuring stable activities in the aluminium sectors for all regions except China. The Chinese aluminium sector will be increased enough to account for the overall global increased aluminium output as calculated in the baseline scenario.

Although theoretically straightforward, the mathematical manipulations required to accomplish this are not, due to the nature of the input-output tables. The fundamental flow matrix, Z, keeps track of the source of all purchases performed by all sectors, as well as the destination sectors of all their sales. Consequently, because "everything is connected to everything" in the flow matrix, single values in it cannot be adjusted without considering implications elsewhere. The following steps outline the method that will be used to impose the assumptions of scenario 1 on the model projections, for each future year n in study:

1. Create x_n, the same way as in the baseline scenario.
2. Create Z_n, the same way as in the baseline scenario.
3. Adjust Z_n by resetting all sales (rows of Z) from all aluminium sectors to their base year values, and transferring the difference to sales from the Chinese aluminium sector, to make a temporary, new matrix $Z_{n,adj}$. If Z has the dimensions $rs \times rs$, where r is the number of regions and s

is the number of industrial sectors in our model, and k is the relevant sector's defined sector number in the matrices, we define the index set $Q = s\{0, 1, 2, \ldots, r-1\} + k$, so that $Z_{n,adj}$ is found as:

$$Z_{ij,n,adj} = \begin{cases} Z_{ij,2000}, & i \in Q \\ Z_{ij,n}, & i \notin Q \end{cases} \tag{3.8}$$

Note that the global aluminium output will be assumed *physically* equal in both scenarios, and so the increased outputs from each region must be converted to tons and then back to euros using Chinese aluminium prices.

4. Construct the resulting new coefficient matrix by combining this temporary flow matrix with the total output vector from the baseline scenario using the equation:

$$A_n = Z_{n,adj}\hat{x}_n^{-1} \tag{3.9}$$

The resulting coefficient matrix will give the same technologies as the original one, but with each sector importing relatively more of their required aluminium inputs from the Chinese aluminium sector.

5. Calculate a new flow matrix and vector of outputs as in steps 1 and 2 by imposing the final demand calculated in the baseline scenario on the new coefficient matrix.

6. Calculate emission structures from the new economical flow matrices.

Referring to the stepwise procedure listed above, it should be noted that the new Z matrices will in fact not be 100% true to the scenario definitions. Rather, a series of new A and Z matrices should be calculated iteratively. This discrepancy is, however, assumed to be negligible in this study.

3.2.3 Scenario 2: Phasing out Norwegian aluminium production

Scenario 2 is basically a minor extension to scenario 1. In scenario 2, the assumption of a shift towards Chinese aluminium production remains the same, but on top of this the Norwegian aluminium industry is assumed to decline steadily from its output in the year 2000 until it reaches zero output in 2030. The reduction in Norwegian aluminium output will hence be countered by a corresponding increase of its Chinese counterpart.

Chapter 4

Building the MRIO Model

4.1 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 *et al.*, 2008), such a system was constructed using ESA data 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.

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

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

4.2.1 Data collection

The challenge in modelling monetary flows within a country as well as between different regions of the world is to deal with the myriad of sources that are available, trying to connect them with relevant adjustments. Among others, sources that have been used for the construction of those matrices are: the European Union's Statistical Office (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 similar for all of European countries: tables of 59 NACE (Nomenclature des Activités Economiques dans la Communauté Européenne) 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 made. This is mentioned in section 4.2.5. 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 were used for this purpose, as it uses an 87 region world trade model. Throughout the compilation of those matrices into a bigger one, currency conversion had to be 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 were available for each country: domestic and import trade flows. Note that the acronym "EU23" refers to the group of countries that are listed above.

4.2.2 Approach

Computing Z^d_{ii}

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

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

The method used to obtain the $Z^m_{ij,i\neq j}$ (import) matrices was a breakdown of the import flows from Eurostat database's Z^m's. Pretty accurate information can be found in the GTAP data about each country's import shares. Unfortunately the sector disaggregation (57 × 57) used in this database was different from the NACE-based classification that was to be used in the final output matrix (59 × 59). A bridging operation from 57 × 57 to 59 × 59 had to be performed 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 ($b^c_{GTAP\rightarrow ESA}$, where c can be any of the considered countries) consists of a void matrix (output dimension × input dimension, or vice versa) with ones wherever two sectors match. Furthermore, row disaggregation must be performed when a GTAP sector has to be distributed into more than one ESA sector. Shares are obtained from the y^e (export demand) in the ESA data. Formally,

$$b^c_{ij} = \frac{b^c_{ij,unit} y^e_i}{\sum\limits_{1\leq i\leq 59} b_{ij,unit} y^e_i} \tag{4.1}$$

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

where b^c_{ij} is the element at row i and column j from the bridge matrix for country c. Besides, $b_{ij,unit}$ represents the element (i, j) of a bridge matrix with only zeros and ones, being in fact more of a correspondence matrix.

As far as the shares are concerned,

$$\text{shares}_{\text{GTAP},ij} = \frac{\check{Z}_{\text{GTAP},kl}}{\sum\limits_{1 \le j \le 87} \check{Z}_{\text{GTAP},kl}} \tag{4.2}$$

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

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

Consequently,

$$shares_{ESA} = b^c_{GTAP \to ESA} shares_{GTAP}$$

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

4.2.3 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. To this end, a "rest of the world" (ROW) layer was added by the attachment of 8 additional regions. 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. The Middle East (ME),
8. Africa (Af).

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

Electricity disaggregation

Electricity production is dealt with as only one sector in the ESA data. However, a disaggregation of this sector is preferable, since different sources are available. Furthermore, the 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 6 different sectors according to energy source. Information about electricity source mixes can be found in appendix C, as retrieved from IEA (2009). The electricity sectors are:

- Hard coal,
- Hydropower,
- Nuclear,
- Wind,
- Natural gas,
- Petroleum and NEC.

To do so, a particular treatment is 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 are actually 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 should not be used by the wind power sector, and uranium and thorium are only used as inputs to the nuclear power plants.

Row disaggregation This part of the work was pretty straightforward; it consisted 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 were 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, columnwise. Table 4.1 presents the way inputs were broken down. Each "×" was substituted by the energy mix share of each source, relatively to the other sources which show an "×" on the same row. Basically the sum of each row must always equal 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 could not 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 4.1, a distribution over all electricity sources has been made, according to energy shares. At this stage, European countries had 64×64 sectors matrices and rest of the world countries were represented by 62×62 matrices.

The Z_{bb} matrix can be represented as in figure 4.1.

$$
\begin{array}{ccccc|ccc}
\multicolumn{5}{c|}{\overbrace{\hspace{12em}}^{\text{EU23, 64 sectors}}} & \multicolumn{3}{c}{\overbrace{\hspace{8em}}^{\text{ROW, 62 sectors}}} \\
Z^d_{AT} & Z^m_{AT\to BE} & Z^m_{AT\to CZ} & \cdots & Z^m_{AT\to UK} & Z_{AT\to Oc} & \cdots & Z_{AT\to Af} \\
Z^m_{BE\to AT} & Z^d_{BE} & Z^m_{BE\to CZ} & \cdots & \vdots & Z_{BE\to Oc} & \cdots & Z_{BE\to Af} \\
Z^m_{CZ\to AT} & Z^m_{CZ\to BE} & \ddots & & \vdots & \vdots & & \vdots \\
\vdots & & & \ddots & \vdots & \vdots & & \vdots \\
Z^m_{UK\to AT} & \cdots & \cdots & \cdots & Z^d_{UK} & Z^m_{UK\to Oc} & \cdots & Z^m_{UK\to Af} \\
\hline
Z^m_{Oc\to AT} & \cdots & \cdots & \cdots & Z^m_{Oc\to UK} & Z^d_{Oc} & \cdots & Z^m_{Oc\to Af} \\
\vdots & & & & \vdots & \vdots & \ddots & \vdots \\
Z^m_{Af\to AT} & \cdots & \cdots & \cdots & Z^m_{Af\to UK} & Z^m_{Af\to Oc} & \cdots & Z^d_{Af}
\end{array}
$$

Figure 4.1: Disposition of national matrices in the MRIO Z matrix.

4.2.4 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

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

Table 4.1: Way the economic flows towards electricity sectors were allocated between 6 different sources. From Hawkins (2009).

written:

$$A = \tilde{Z}\hat{g}^{-1} \tag{4.3}$$

4.2.5 Assumptions

Along the compilation, a non-negligible number of assumptions have been made, described 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 was 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 was 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 made when the other SIOTs 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 must unavoidably be considered when it comes to disaggregating the electricity sectors. First of all, the physical flow shares were used to split the row “Electricity production”. This means that the electricity price is constant regardless of what the means of production are. Secondly, the same energy mix was used when two electricity production sectors (or more) have requirements from the same sector. Finally, some sectors belonging to the same “ESA group” should be accounted differently from source to source, e.g. the sector “land transportation” comprises railway, road and pipeline transportation. Last, but not least, the currency conversion was made according to the average euro rates over year 2000; there is no way to take the rate fluctuations into account as the Z matrices give total flows along the year.

4.3 Compilation of the S matrix

A stressor matrix providing industry specific environmental data for all European countries in the multiregional input-output table were made using the NAMEA (National accounting matrices with environmental accounts) 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, 2009). Thus, the NAMEA framework provides environmental data in physical units, which is congruent with a national accounting system and nomenclature using monetary accounting (OECD, 2005). This makes it a suitable tool for environmental input-output analysis. Data from the NAMEA framework were also supplied with country-specific environmental data from the Eurostat database where data were lacking.

The stressors included in the stressor matrix are CO_2, CO, N_2O, CH_4, NH_3, NO_x, NMVOC[1] and SO_x. The stressors in the NAMEA framework were consistently compiled with the way economic activities are represented in the national account system used in the input-output table, but a higher order of sector aggregation was occasionally used. This made sector disaggregation necessary 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 had different levels of detail accurateness. Therefore individual disaggregation of sectors for each country was necessary. Disaggregation was performed based on total output shares derived from the Eurostat database.

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.

The electricity sector was disaggregated into six electricity sources in order to get more specific data on electricity generation from the stressor ma-

[1]Non-methane volatile organic compounds

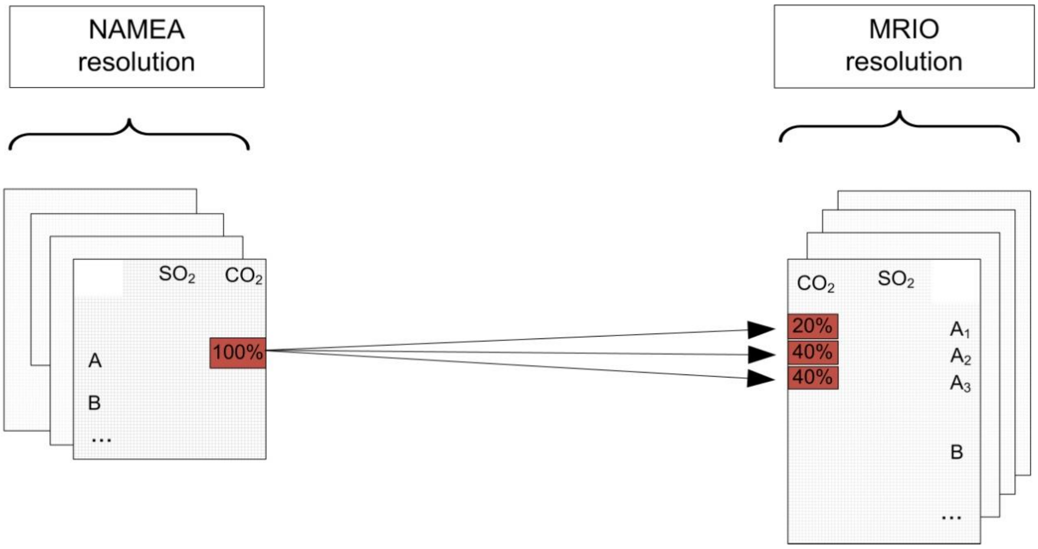

Figure 4.2: Graphical representation of the disaggregation of sectors using the total output shares derived from Eurostat.

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

Table 4.2: Proxy countries used for the S matrix modeling.

trix. This required specific emission data, which was taken from the Ecoinvent database (Frischknecht & 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.

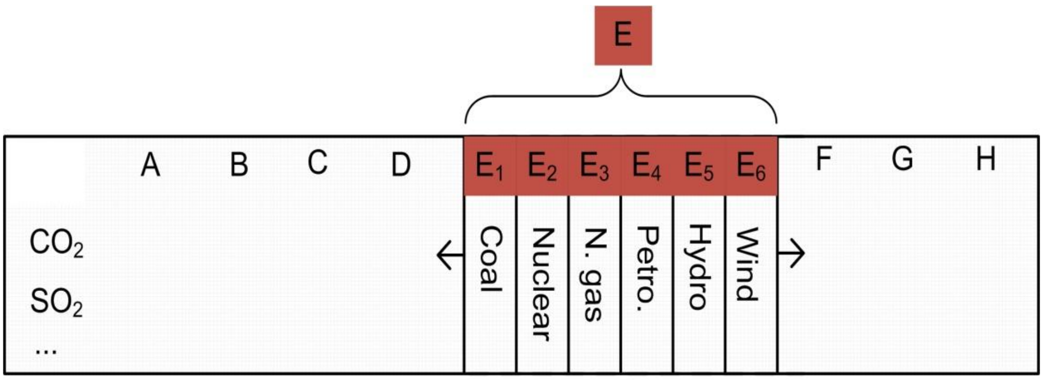

Figure 4.3: Graphical representation of the disaggregation of the electricity sector, in order to obtain more specific environmental data regarding energy use.

4.4 Data quality

The quality of the data overall should be fairly good, at least satisfactory for this study. In the Z table, the main assumption made was the import shares (representing interregional trade patterns), which were estimated from corresponding shares from the older GTAP database. This database was also the source of the data 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 sectors altogether. These holes had to be filled by means of disaggregation and comparison to similar countries. Care should be taken when applying emission data, especially the less "common" emissions — e.g. CO_2 data are generally more comprehensive than SO_x data. Also, larger countries generally report more data than smaller ones.

4.5 Hybridizing the system to enable aluminium study

The nature of input-output analysis is such that it attempts to include everything in the regional system in study, thus taking care of one of the problems of life cycle assessments — the inevitable incompleteness that arises when the system boundary is drawn. However, this completeness naturally comes with the cost of less detail. In the tables used in this study, the European regions were originally split into 64 economical sectors. This meant that the aluminium sector was part of a larger aggregate sector called "Manufacture of basic metals". In order to enable a utilization of the input-output database to study a certain product of interest, like aluminium, the system should be expanded. This expansion should at least include the sector producing the product in study, and preferably one or more additional sector representing key suppliers. These additional sectors constitute what is called the foreground system, whereas the original sectors represent the background system.

For this study, a foreground system consisting of three sectors was chosen. As explained in the previous chapter, primary aluminium production inherently consists of three main steps, each of which gave rise to a foreground sector in this study: Primary aluminium smelting, alumina refining and bauxite mining. For each foreground sector, a *parent* sector in the original tables was identified, in which the foreground sector was originally included. This was necessary because of the relatively large size of the foreground sectors, which would lead to unacceptably large double count errors, had not the parent sectors been reduced as the foreground sectors were created. Table 4.3 summarizes the foreground sectors and their parent sectors.

Sector name	**EU parent sector**	**ROW parent sector**
Primary aluminium	21: Manufacture of basic metals	36: Metals nec
Alumina	21: Manufacture of basic metals	36: Metals nec
Bauxite	7: Metal ores	18: Minerals nec

Table 4.3: Foreground sector specifications

For simplicity, the foreground sectors were initially assumed to employ the same technology as their parent sectors, meaning their sale and purchase patterns were assumed to be the same. Some key adjustments were later imposed on the resulting table entries to increase their accuracy. In order to determine the size of each foreground sector in each of the regions, the physical output of each of the foreground sectors' products for every country was found using the United Nations Industrial Commodity Statistics Database (United Nations, 2009b). As the existing input-output tables represent flows of goods and services as monetary flows, price data for each foreground sector's output had to be estimated. This was done using the United Nations Commodity Trade Statistics Database (United Nations, 2009a), where exports of each product in physical as well as monetary terms from each country are listed. As soon as the value of the total output of each foreground product from each region was estimated, this could be expressed as shares of their respective parent sectors' output as calculated from the original input-output tables. The share a any given foreground sector f constitutes of its parent sector p, then, is the ratio of the monetary value of their outputs x over the reference time period:

$$a = \frac{x_f}{x_p}$$

The process of expanding the existing input-output tables to include the foreground sectors defined in table 4.3 can be summarized in the following steps:

1. The original input-output flow matrix (Z) was expanded with three extra rows and columns for each of the 31 regions to represent sales to and from the foreground sectors.

2. Sales and purchases (i.e. row and column entries) for the foreground sectors were entered as a share a of the parent region-sector output according to the ratio of output in monetary units as explained above. Any foreground region-sector that did not have any activity in 2000, simply resulted in all-zero vectors.

3. Parent region-sectors' row and column entries were decreased accordingly, to make the totals remain unchanged.

4. Flows within the foreground system, represented in Z as the 3-by-3 sub matrices A_{ff} where the new columns intersect, were inserted manually using LCI data adapted from Steen-Olsen (2008), so that the aluminium sector were given inputs from the alumina sector, which in turn had inputs from the bauxite sector. The remaining elements were set to zero.

5. Some key inputs to the aluminium sectors from the background system were subsequently adjusted according to LCA data from Steen-Olsen

(2008). Electricity inputs were increased, and European aluminium smelters were assumed to get their alumina from refineries in North and South America, as is commonly the case. Also, inputs from the sea transport sector were adjusted to fit these assumptions. Internal foreground system flows were otherwise assumed to be domestic flows.

6. The final demand, stressor and value added matrices Y, S and V were subsequently expanded with extra rows (Y) or columns (S, V) in the same fashion.

Figure 4.4 attempts to describe graphically the manipulations performed. The reader is further referred to the Matlab codes in the appendix for more details on the calculations.

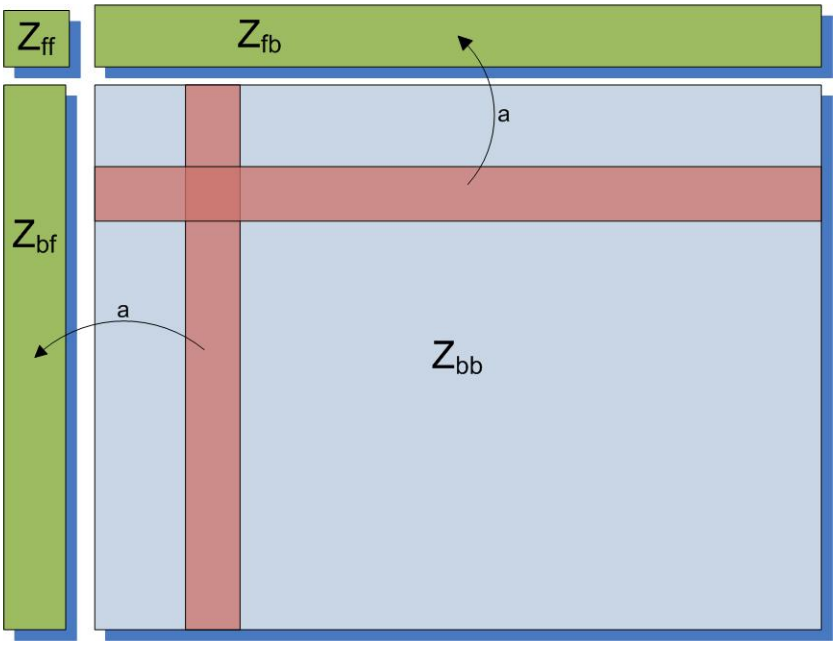

Figure 4.4: Sketch of the process of expanding Z by disaggregating one or more sectors.

Chapter 5

Results

This chapter will lay out the most important results from this study and analyze them. It starts out by examining the model's representation of the present global aluminium industry and its associated environmental consequences, before moving on to the future projections for the three scenarios.

5.1 Model results for the base year 2000

Total specific emissions from aluminium production

Upon expanding the input-output tables to include the foreground system and calculating the resulting Leontief inverse, the model accuracy was tested by demanding 1 ton of aluminium from the Norwegian, German and Chinese aluminium sectors and studying the resulting GHG emissions. Norway and Germany were chosen because these were specifically analyzed in the life cycle assessment of Norwegian primary aluminium production by Steen-Olsen (2008), which was the source of the life cycle inventory data used to model the aluminium sector in this study[1]. Apart from the flows estimated from those LCI data, the aluminium sector was assumed to have the same technology as the original "basic metals" sector, hence the calculated emissions per ton final demand of primary aluminium should correspond fairly good with the results obtained there. The Chinese aluminium industry was also scrutinized, due to its rapidly increasing share of the global aluminium output and its consequent central role in the scenarios modeled here. The resulting emissions for Norway, Germany and China are shown in table 5.1.

As shown in the table, total GHG emissions incurred due to a final de-

[1]Note that the LCI for European smelters use values from 1997/1998, while the present system takes 2000 as its point of departure.

Emission source	**Norway**	**Germany**	**China**
Aluminium smelting	4.51	4.22	4.29
Alumina refining	1.18	1.31	1.33
Electricity production	1.66	11.42	18.83
Transport	0.41	0.41	0.07
Other	0.70	1.30	5.57
Total	**8.46**	**18.66**	**30.10**

Table 5.1: GHG emissions (tons of CO_2-eq) per ton final demand of primary aluminium, distributed according to emitting sector

mand of one ton aluminium from the Norwegian sector amounts to 8.46 tons. In the life cycle assessment by Steen-Olsen (2008), the GHG emissions were estimated to 8.92 tons CO_2-eq. This 5% deviation was considered acceptable. Corresponding emissions for aluminium demanded from the German and Chinese aluminium sectors came out as 18.66 and 30.10 tons CO_2-eq, or 2.2 and 3.5 times the Norwegian case, respectively. Table 5.1 clearly shows that emissions related to electricity production make most of the difference, as would be expected. The same tendency is suggested in Steen-Olsen (2008), where a simulated relocation of a Norwegian aluminium smelter to Germany resulted in 2.5 times higher greenhouse gas emissions, due to more emission intensive electricity production.

Total per unit final demand emissions of seven modeled stressors for the aluminium sector in the aluminium-producing regions are shown in table 5.2, together with the corresponding GWP and AP. NH_3 emissions were also included in the data set, but due to data incompleteness and the limited relevance of these emissions in primary aluminium production, they were not included here. This study focuses primarily on GWP, to which CH_4, CO_2, PFC (aggregated with CO_2 in this study) and N_2O contribute, and on AP, which is determined by emissions of NO_x and SO_x. Note that Italian emissions are unrealistically high, probably due to background data or modeling errors, and were disregarded.

The specific GHG emissions are overall quite low in Western European countries such as Norway, Sweden and France, while they are high in the Middle East, China and Africa. Regarding acidification contributors, Africa and China are the highest emitters, while the Middle East performs relatively better. In the lower end, we find Norway and Sweden as we did for GHG emissions, as well as the "Rest of Europe" aggregate region. Generally, the specific emissions listed in table 5.2 reflect the electricity mixes in the regions, as suggested by table 5.1. As examples, Norway is modeled with virtually no

Region	**CH_4 (kg)**	**CO_2+PFC (tons CO_2-eq)**	**N_2O (kg)**	**NO_x (kg)**	**CO (kg)**	**NMVOC (kg)**	**SO_x (kg)**	**GWP (ton CO_2-eq)**	**AP (kg SO_2-eq)**
Austria	39.9	12.6	0.407	37.2	498	16.3	41.6	13.6	68.5
Czech Republic	15.2	17.2	0.491	48.0	587	16.6	44.6	17.7	77.5
France	15.9	9.2	0.308	36.5	554	13.8	44.8	9.7	71.9
Germany	22.2	18.0	0.570	41.0	510	13.9	46.4	18.7	76.1
Hungary	43.7	15.4	0.708	45.1	506	26.2	76.3	16.6	114.1
Italy	1004.3	63.6	5.223	290.3	1650	742.8	378.6	88.2	599.5
Netherlands	23.1	23.9	0.737	49.4	519	15.3	46.1	24.6	80.0
Norway	35.2	7.3	1.119	31.2	439	10.3	28.9	8.5	50.4
Poland	31.7	27.2	0.510	70.6	490	14.9	127.0	28.0	187.7
Slovakia	32.9	15.1	0.818	45.9	571	27.3	62.7	16.1	98.2
Spain	33.5	19.1	0.626	77.1	627	29.8	106.8	20.4	166.7
Sweden	25.5	8.4	0.301	33.5	487	12.0	39.0	9.0	63.6
United Kingdom	24.4	23.5	0.858	48.1	530	14.3	53.6	24.3	88.4
Oceania	26.7	20.6	0.405	43.5	2156	16.3	95.4	21.3	136.2
China	60.3	28.4	1.059	94.7	666	20.2	204.1	30.1	292.3
Asia	49.1	25.6	0.814	54.4	1015	27.2	108.4	27.0	157.3
North America	23.0	23.5	0.401	54.2	280	9.1	112.3	24.1	161.8
South America	49.6	12.9	0.795	25.8	4170	43.6	43.6	14.3	65.3
Rest of Europe	34.9	14.3	0.612	16.7	310	19.0	50.2	15.3	68.7
Middle East	101.2	37.9	3.084	47.9	705	26.8	101.2	41.1	145.4
Africa	69.1	32.5	1.517	101.7	5418	48.7	169.1	34.6	253.8

Table 5.2: Tons of emissions and total GWP and AP per ton final demand of primary aluminium for the producing regions, as estimated by this model.

electricity production other than hydropower, and more than three fourths of the French electricity production is nuclear powered. Although both (and all other) regions import and export some electricity, this greatly influences the specific emissions from the domestic aluminium industries. In the upper end of the scale, China is modeled as producing electricity that is 80% coal-based. For detailed information on the electricity mixes assumed in this study, the reader is referred to section C of the appendix.

Model representation of the global aluminium industry

By extracting values from Z, the input-output tables' representation of the global aluminium sector for the year 2000 can be evaluated. Aggregated figures are listed in table 5.3. Note that aluminium that goes to final demand is not included for simplicity. However, aluminium is generally not consumed as a final product, so much as being used as inputs to other industries producing manufactured goods, and so the values are not much affected by this exclusion (compare to figure 5.1, which shows that the total output in 2000 was modeled as 23.8 million tons, suggesting that some 93% is consumed by industries).

Region	**Prod.**	**Cons.**	**Imports**	**Exports**	**Net Exp.**
Europe	4258.5	5019.1	1161.0	400.5	-760.5
Oceania	1725.8	376.5	40.8	1390.1	1349.3
China	2642.0	2961.8	494.3	174.4	-319.8
Asia	5069.6	5740.6	1442.5	771.6	-671.0
North America	5314.1	5837.1	875.6	352.6	-523.0
South America	1619.4	928.6	39.1	729.9	690.8
Middle East	591.1	834.5	339.1	95.7	-243.4
Africa	1008.5	531.0	96.3	573.8	477.5
Totals	**22229.0**	**22229.0**	**4488.6**	**4488.6**	**0**

Table 5.3: Global production, consumption and trade of aluminium (except final demand) for the base year 2000. All values in kilotons.

As shown in the table, total primary aluminium output (consumed by industries) in the world in the year 2000 amounted to 22.2 million tons in this model. North America and Asia were the biggest producers, each producing more than five megatons. South America, Africa and especially Oceania were net exporters, while the remaining regions had a production deficit and required imports to satisfy their demands. All in all, some 4.5 Mt of primary aluminium were subject to long-distance trade (i.e. from one major region to another), corresponding to 20% of all primary aluminium produced.

5.2 Scenario 0: The baseline

By imposing the expected GDP growth on the input-output model, simulations of the global economic flows in 2010, 2020 and 2030 were obtained. Following the trend in projected GDP, total global output more than tripled over the period in the model simulation. As expected, the large economic growth results in correspondingly increased emissions in a world that is otherwise equal. Figure 5.1 shows the total global output of aluminium as projected by this model.

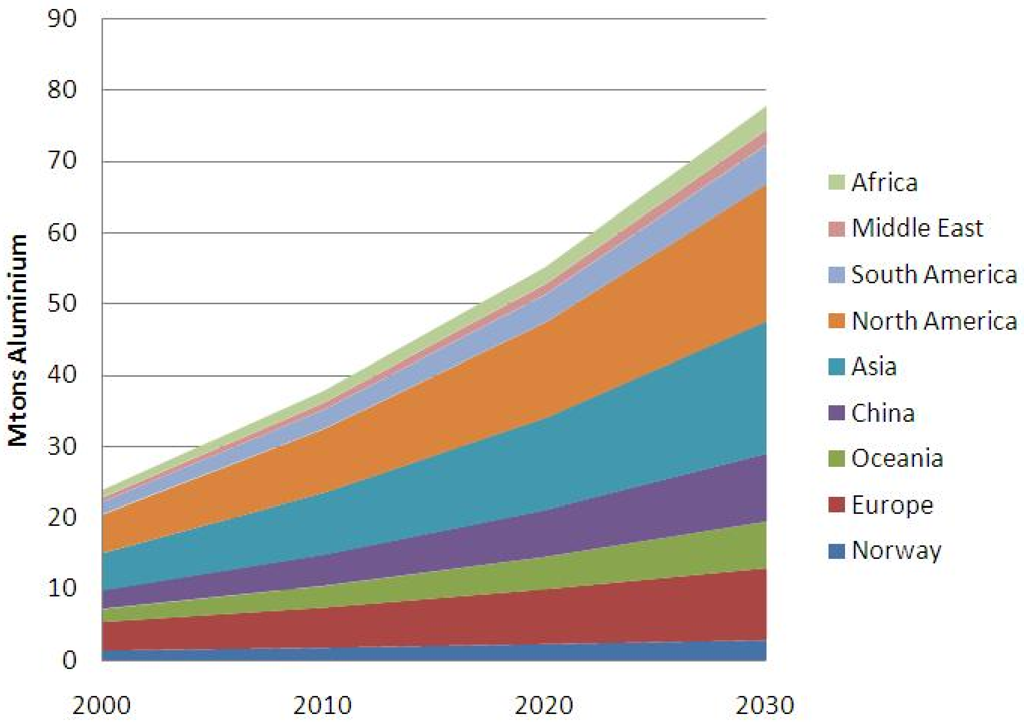

Figure 5.1: Projected global output of Aluminium, 2000–2030. Values in million tons.

Over the three-decade period simulated, the output is more than tripled, from 23.8 million tons in 2000 to 77.7 million tons in 2030. This corresponds to an annual increase of just over 4% on average. Note that the total global aluminium output projections apply to all three scenarios, and so the output graph is shown only in the present section. What changes is the geographical location of this production — i.e. which regions will increase their production to satisfy the future demand?

The relative distribution of the origin of the aluminium produced globally is shown in figure 5.2. As the final demand projection is the sole driving parameter in the baseline projection, while all technologies, trade and patterns and other factors were assumed unchanged, the small relative changes are as expected.

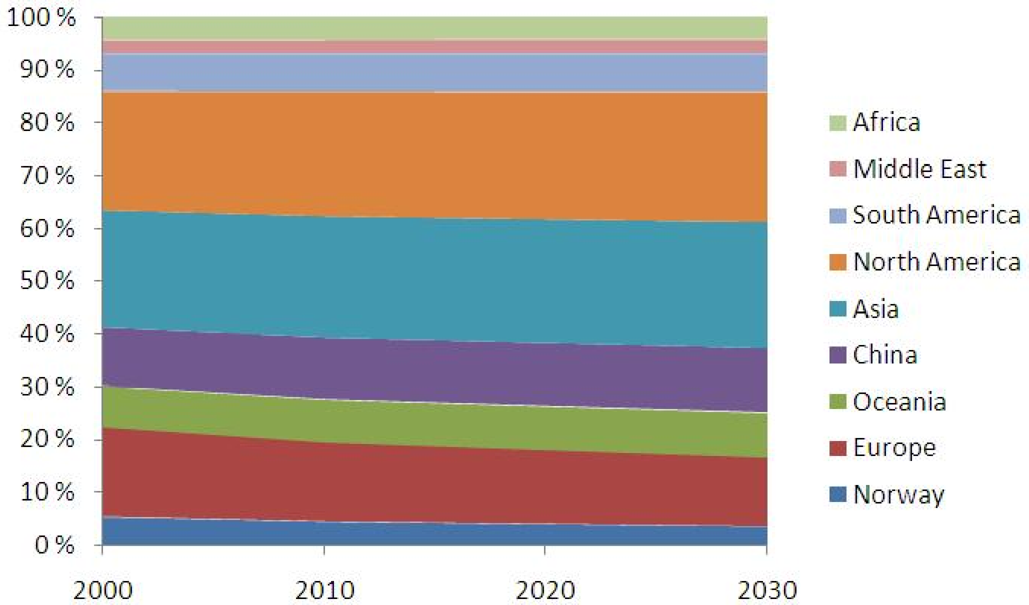

Figure 5.2: Regional shares of total global aluminium production 2000–2030, scenario 0.

In the base year 2000, 22.6% of the aluminium produced globally was North American, while Europe and Asia (except China) followed close behind with 22.4% and 22.1%, respectively. The Norwegian production was 5.4% of the total, almost a quarter of the overall European output. Although fairly stable, this distribution can be seen to change somewhat, due to unequal growth rate expectancies. By 2030, the European share of global aluminium output has decreased to 16.6%, while North America and Asia consolidates their leading position, boasting 24.8% and 23.9%, respectively. China's and Oceania's output shares are also expected to rise somewhat, while the shares of South America, the Middle East and Africa remain stable.

In the field of industrial ecology, one emphasizes the need to link emission data to international trade flow data. As industrialized countries tend to source out labour intensive manufacturing to low-cost countries, simply comparing direct emissions for various regions will generally not provide a satisfying image of the underlying causes of these emissions. Following this reasoning, it is of interest to study the origin of the aluminium that is used as inputs to European industries, and how this evolves in the various scenarios. Figure 5.3 shows the relative distribution of aluminium consumed by European industries by region of origin.

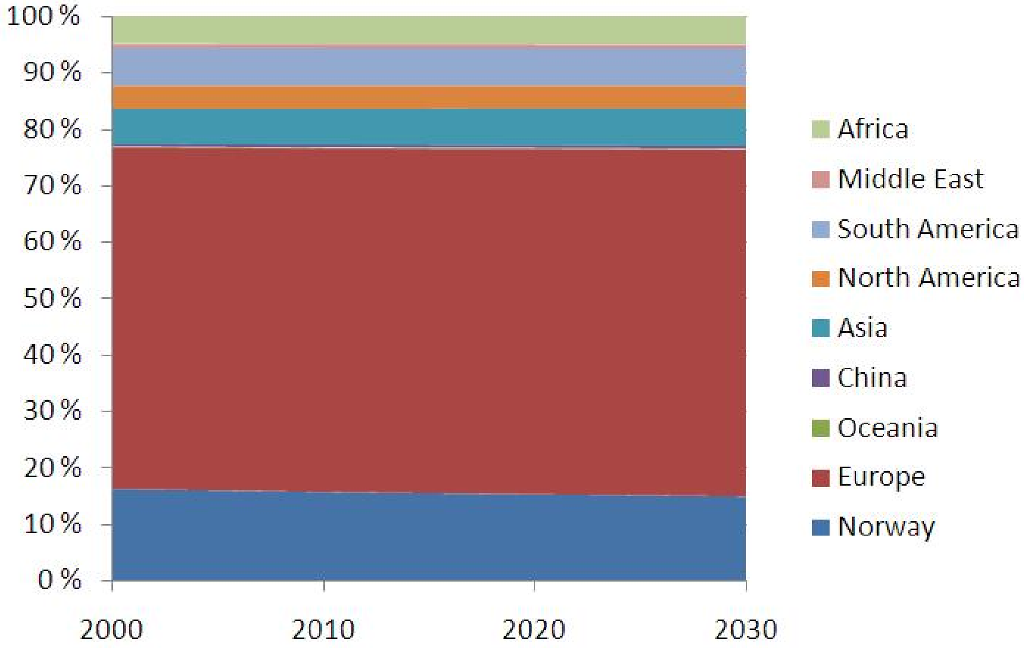

Figure 5.3: The geographical origin of the total aluminium consumption in Europe 2000–2030, as simulated in scenario 0. The graph shows regional shares relative to the total.

Following the same logic as above, it is not surprising that the same monotony is exhibited by figure 5.3 as was the case in figure 5.2. In 2000, 76.9% of the European industry demand for aluminium was satisfied locally (of which 16.4% were Norwegian), decreasing to 76.4% in 2030. Asia and South America supplied most of the imports, by around 6–7% each.

The environmental consequences associated with the total global aluminium production over the three decade period in the baseline scenario are shown graphically in figure 5.4, with respect to GWP and AP. In the base year 2000, these were calculated to 493 Mt CO_2-eq and 3.22 Mt SO_2-eq.

Figure 5.4 shows relative increases for both impact categories that basically correspond to the increase in global aluminium output. In 2030, the GWP were estimated to 1621 Mt CO_2-eq, and AP to 10.7 Mt SO_2-eq — both are about 3.3 times higher, corresponding to an average annual increase of just above 4%, as was the case for total aluminium output.

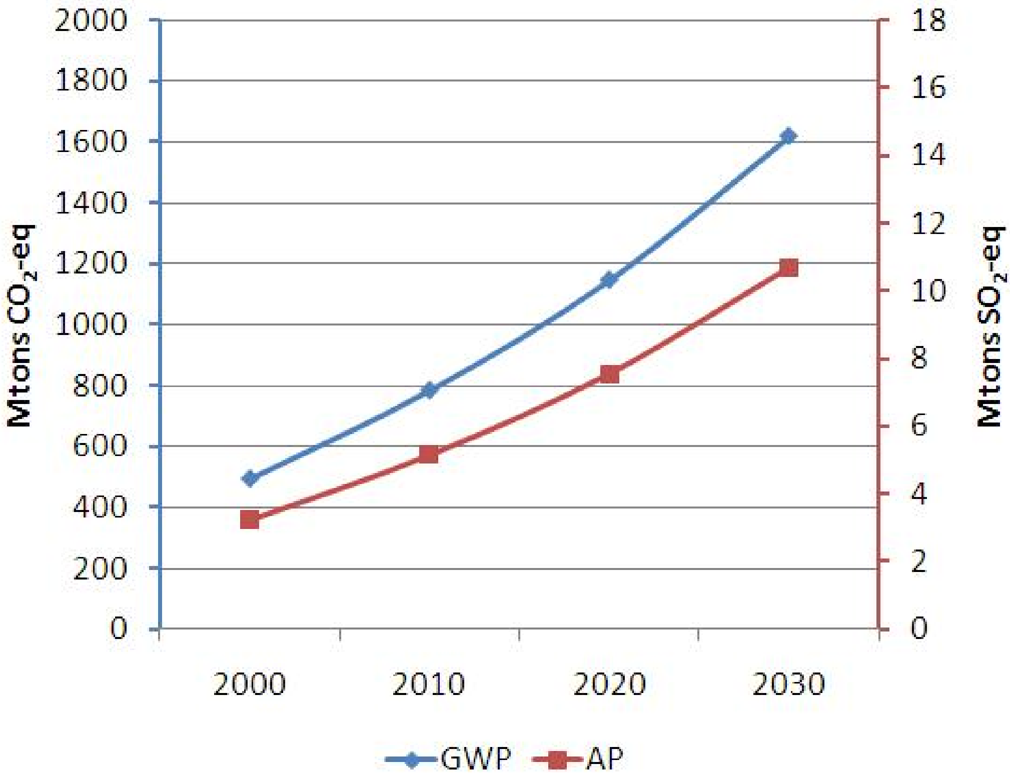

Figure 5.4: Global warming potential and acidification potential from emissions due to primary aluminium production from 2000 to 2030, scenario 0.

5.3 Scenario 1: Shift towards Chinese aluminium

In scenario 1, all the increased aluminium production that was projected in the baseline scenario was assumed to take place in China. As discussed in section 5.1, emissions per unit final demand of aluminium were found to be relatively high in China, hence we would expect this shift to lead to larger emissions than those found in the baseline scenario. In the base year 2000, the Chinese output of aluminium represented a modest 11.2% of the total global output (see section B of the appendix for aluminium production data). At the same time, in the baseline scenario simulation the global output was expected to more than triple over the three decades studied. This implies a total shift in the global aluminium sector, where Chinese aluminium moves to dominate the global aluminium market, accounting for 73.0% of the production by 2030. Figure 5.5 graphically shows this shift. Recall that in the baseline scenario, these shares were more or less constant.

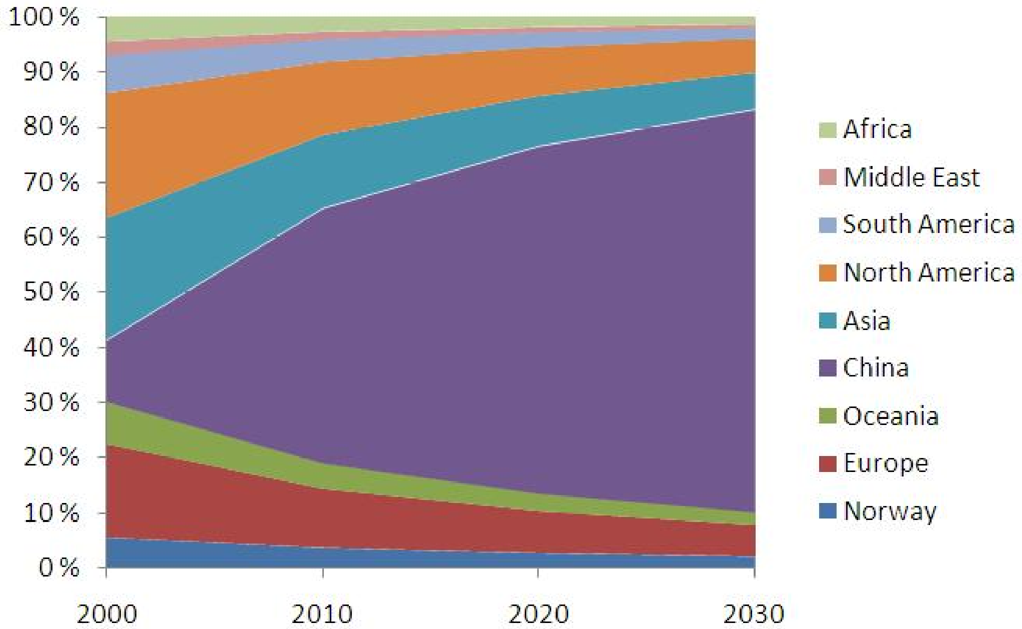

Figure 5.5: Regional shares of total global aluminium production 2000–2030, scenario 1.

As scenarios 1 and 2 assumed the same consumption development trend as the baseline, the European aluminium consumption increases at the same rate for all the three scenarios. The fact that an increasing share of the aluminium produced globally originates in China in scenarios 1 and 2, necessarily implies that more of the other regions' consumed aluminium will be

Chinese, because their industrial and final demand for aluminium increase more rapidly than their domestic output of aluminium. Figure 5.6 depicts this transfer for Europe.

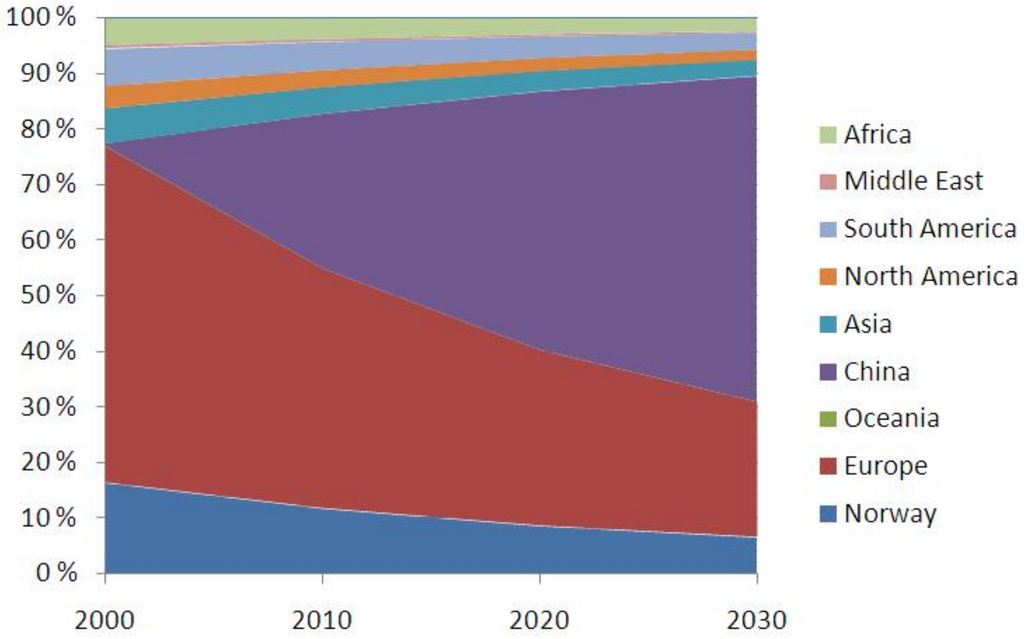

Figure 5.6: The geographical origin of the total aluminium consumption in Europe 2000–2030, as simulated in scenario 1. The graph shows regional shares relative to the total.

In the base year 2000, Europe was to a large degree self-sufficient with aluminium, while the share of Chinese aluminium into Europe was almost negligible. The shift is dramatic — by 2030 the Chinese aluminium share has risen to 58.7%, while the domestic share has decreased from 76.9% to 30.9%. By interpolating between the data points in figure 5.6, estimates can be obtained that show Chinese aluminium surpassing local aluminium as the main source for aluminium consumption in Europe by 2018, and by 2022 more than half of the total European consumed aluminium will be Chinese, according to this scenario.

Figure 5.7 shows the environmental impacts resulting from the situation modeled in scenario 1. The effects of the shift towards Chinese aluminium are evident. We see that projected total GWP and AP in 2030 are considerably higher than they were in scenario 0, 1806 Mt CO_2-eq and 16.0 Mt SO_2-eq, respectively. For GWP this is a 3.7 times increase — and for AP as much as 5.0 times the impacts projected in the baseline scenario. Compared to the baseline scenario's emission projections for 2030, this means that the

GWP in scenario 1 would be 11.4% higher and the AP 50.0% higher. This reflects the fact that Chinese electricity is mostly coal-based, which is the electricity source with the highest emissions of NO_x and SO_x per kilowatt hour (Frischknecht & Jungbluth, 2007).

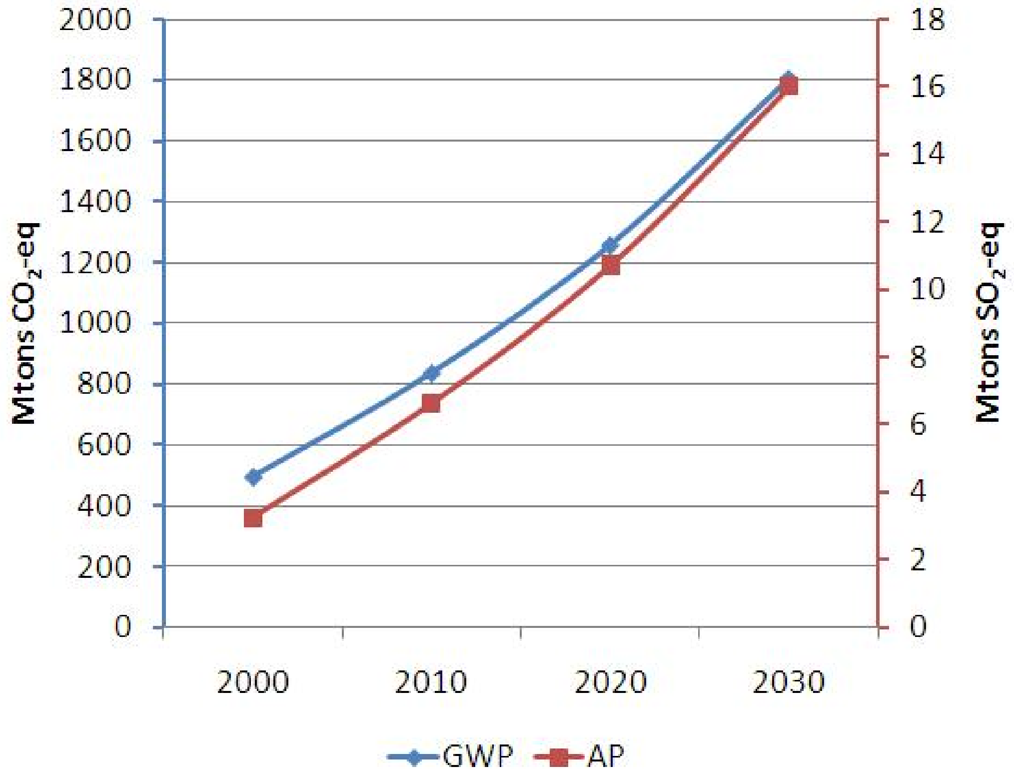

Figure 5.7: Global warming potential and acidification potential from emissions due to primary aluminium production from 2000 to 2030, scenario 1.

5.4 Scenario 2: Phasing out Norwegian aluminium production

Scenario 2 employed the same assumptions as scenario 1, with the additional one that Norwegian output of primary aluminium would decline steadily from its year 2000 level, reaching zero output in 2030. This scenario would hopefully give an idea of the importance of the Norwegian aluminium industry for the Norwegian economy as a whole, as well as for the emission profile of the global aluminium industry.

The decline of Norwegian aluminium production in scenario 2 is shown in figure 5.8, where each region's aluminium output relative to the global total is displayed. Compared to figure 5.5, which show the same projections for scenario 1, the difference is basically that the Norwegian share declines from 5.4% of the global output in 2000 to 0% in 2030 in scenario 2, while Norwegian aluminium constituted 1.9% of the total output in 2030 in scenario 1. The difference is picked up by China, which increases its 2030 share from 73.0% in scenario 1 to 74.8% in scenario 2.

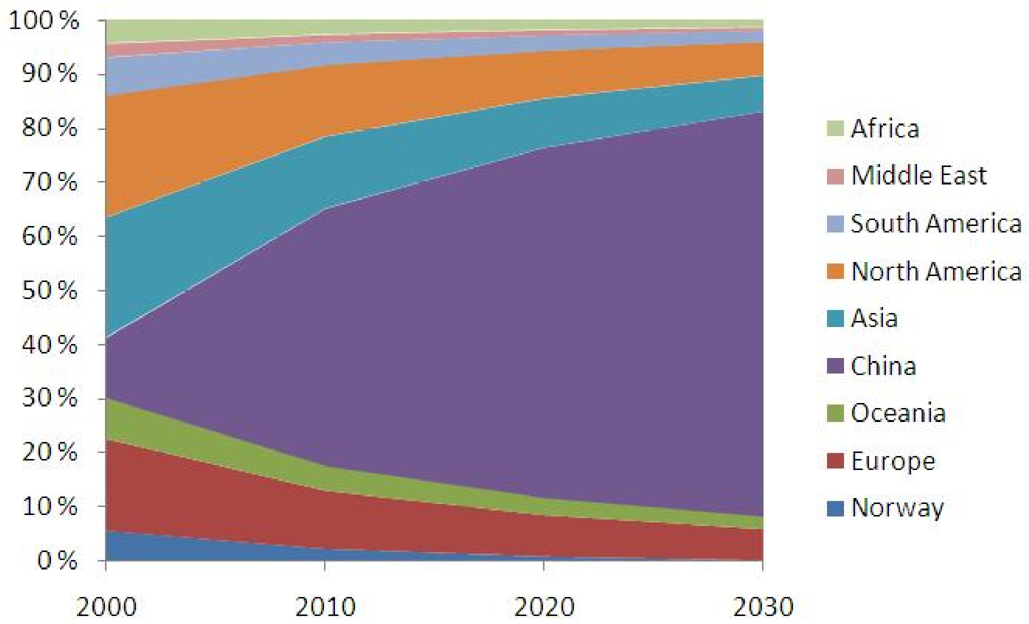

Figure 5.8: Regional shares of total global aluminium production 2000–2030, scenario 2.

Figure 5.9 shows the origins of aluminium consumed by European industries. It displays the same main features regarding imports as figure 5.6 for scenario 1, but the fact that Norwegian aluminium production is diminishing implies that even more must be imported from other regions to satisfy the European demand. In the base year 2000, Norwegian aluminium represented a significant share of the total European consumption (16.4%), more than one fifth of the locally produced aluminium overall. In scenario 1, the Norwegian share had diminished to 6.6% due to the Chinese expansion, while in scenario 2 all this is taken up by China. As such, the Chinese share of aluminium consumed in Europe in 2030 come out to 64.4% in scenario 2, compared to 58.7% in scenario 1.

The environmental impacts of scenario 2 were also larger than in scenario

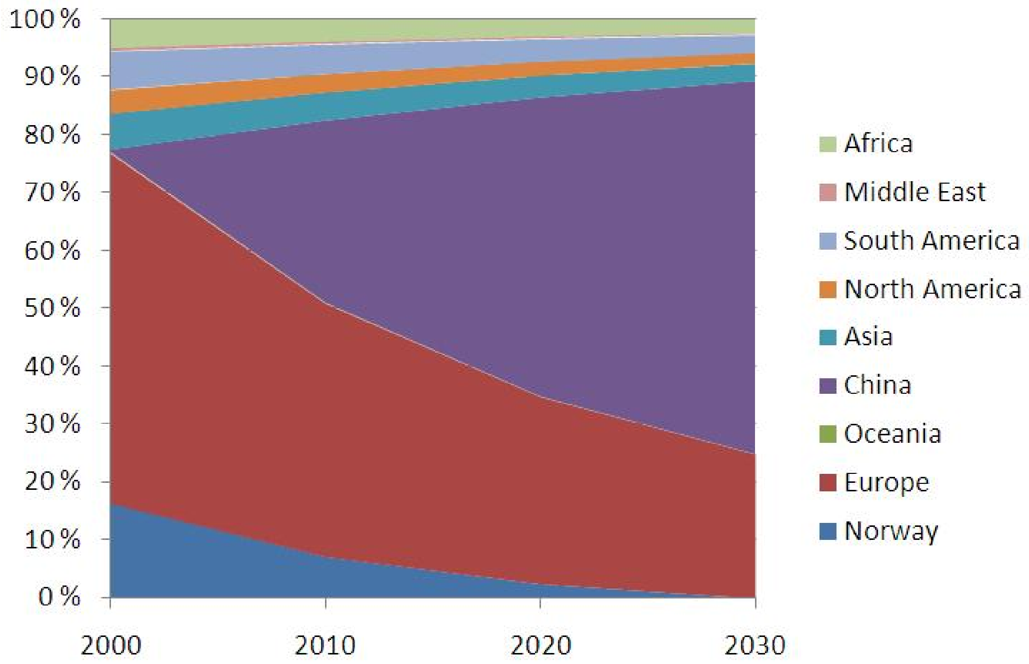

Figure 5.9: The geographical origin of the total aluminium consumption in Europe 2000–2030, as simulated in scenario 2. The graph shows regional shares relative to the total.

1, albeit to a limited extent. In 2030, the total GWP due to the global aluminium production had risen to 1822 Mt CO_2-eq, while AP were at 16.2 Mt SO_2-eq. This is 12.5% and 51.9% higher than what was forecast by the baseline scenario.

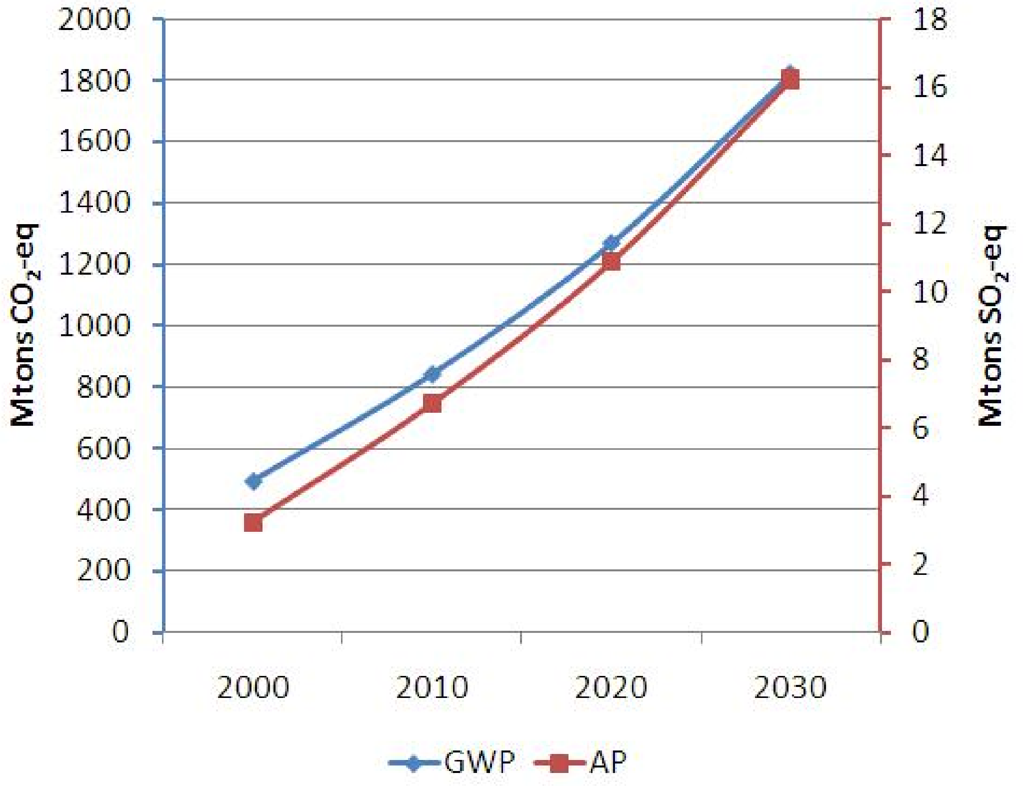

Figure 5.10: Global warming potential and acidification potential from emissions due to primary aluminium production from 2000 to 2030, scenario 2.

Economical repercussions for Norway

In the year 2000, the Norwegian output of aluminium was about 1.3 million tons, with an estimated value in this model of 2.4 billion euros, or about 1.2% of the total Norwegian output of that year. In the baseline scenario, the Norwegian aluminium output was roughly doubled from 2000 to 2030. By contrast, the phasing out assumed in scenario 2 was completed by 2030, leading directly to an output lowered by about 5.1 billion euros. However, as the Norwegian aluminium sector to a large extent makes its purchases from other Norwegian sectors, its decline naturally leads to some economical repercussions all across the Norwegian economy. The extent of this effect was explored by comparing the total output from all the Norwegian economical sectors calculated for the year 2030 in the "business as usual" baseline scenario, to those found in scenario 2. As it turns out, the total Norwegian output in 2030 comes out 7.3 billion euros lower in scenario 2 than in the baseline — 2.2 billions more than the direct output loss from shutting down all the smelters. Although not an accurate economical measurement tool, this still indicates that economical repercussions of such a scenario would in fact influence several other sectors than the aluminium sector itself.

5.5 Scenario comparisons

In conclusion, the three scenarios' respective assumptions and resulting impacts are compared. The previous sections suggested that global emissions due to the industrial and final demand of aluminium would increase substantially as the demand was increasing. Figure 5.11 clearly shows the link between the decline in relative market share of European aluminium, and the corresponding Chinese increase, exhibited by scenario 1 and 2, and the total environmental impacts related to the global primary aluminium industry. As Chinese aluminium moves to dominate the global market, GWP and especially AP increase correspondingly.

Table 5.4 provides a comparison of the three scenarios' individual prospects for the year 2030, summarizing some of the main results analyzed in the present chapter.

Results, 2030	**Unit**	**Sc. 0**	**Sc. 1**	**Sc. 2**
Chinese share of total Al prod.	%	12.2	73.0	74.8
Norwegian share of total Al prod.	%	3.5	1.9	0.0
Domestic Al consumed in EU	%	76.4	30.9	24.9
Norwegian Al consumed in EU	%	15.1	6.6	0.0
Total GWP from Al production	Mt CO_2-eq	1620.5	1805.8	1822.3
Total AP from Al production	Mt SO_2-eq	10.68	16.02	16.22

Table 5.4: Summary of some important simulation results for the year 2030 for each scenario analyzed.

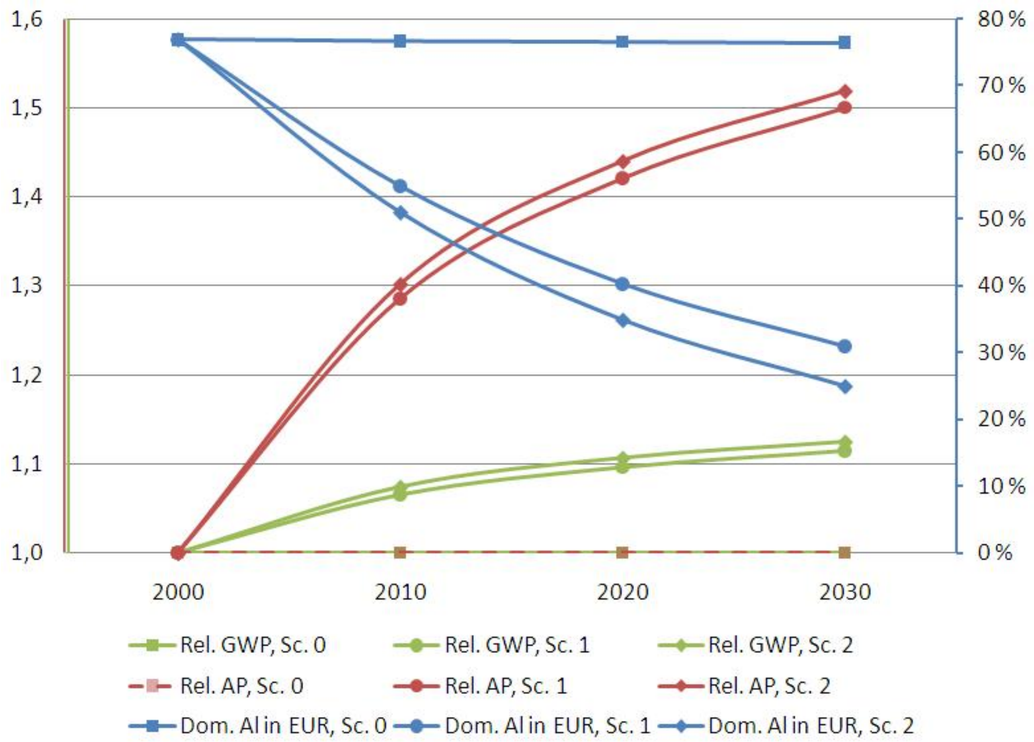

Figure 5.11: Comparison of the scenario developments over the simulated time period. The blue lines show the share of the European aluminium consumption that is domestically produced (right axis), while the red and green lines show the resulting impacts for each scenario relative to the baseline (left axis).

Chapter 6

Discussion and Conclusion

This study set out to construct a multiregional input-output database, and apply this to assess emissions related to European production and consumption activities. A model providing a detailed representation of 23 European countries as well as 8 aggregated sectors representing the rest of the world was created from statistical data. By scaling the model's representation of final demand according to external GDP projections, estimated final demands up to 2030 were calculated and applied to the model. Based on the GDP projections, three scenarios were defined; A baseline scenario and two alternative scenarios, both assuming all new smelter capacity to be installed in China. By adjusting the model to fit these three scenarios, parallel simulations could be run, the environmental repercussions of each scenario modeled and the results compared.

The constructed model provided an overview of the global aluminium industry, its structure and its environmental consequences. The multiregional input-output model proved a useful framework to obtain the goals of the study, by providing an overall overview of the global aluminium sector. Mechanisms, emissions and trade patterns were uncovered, showing not only the direct emissions structures, but also their underlying causes and driving forces.

The model results indicated total emission intensities of primary aluminium production that were very different from one region to another, mainly due to the various energy sources utilized in the regions. GWP came out to 8.46 tons CO_2-eq per ton aluminium for Norway up to as much as 30.1 tons CO_2-eq per ton aluminium in the rapidly expanding Chinese aluminium sector. As for AP, Norway came out lowest again with 50.4 kg SO_2-eq per ton aluminium, while each ton of Chinese aluminium resulted in 292 kg SO_2-eq.

Simulations from 2000 to 2030 showed a global aluminium output that increased about threefold, basically following the assumed increase in GDP.

By 2030, the total global output were estimated to about 78 Mt assuming no changes other than increased overall demand. Environmental impacts related to aluminium production followed suit, increasing from 493 Mt CO_2-eq and 3.22 Mt SO_2-eq in 2000 to 1621 Mt and 10.7 Mt in 2030, respectively, in scenario 0.

Simulation results for the alternative scenarios 1 and 2 showed a future in which Chinese output of aluminium rapidly increases, dominating the global market by 2030 with 73.0% of the output in scenario 1 and 74.8% in scenario 2, from a modest 11.2% in 2000. In line with the high Chinese emission intensities described previously, emissions increased more rapidly in scenario 1 and 2 compared to the baseline, especially concerning AP. For scenario 1, GWP and AP in 2030 were 1806 Mt CO_2-eq and 16.0 Mt SO_2-eq, while scenario 2 yielded 1822 and 16.2 Mt, respectively. A closer look at the Norwegian economical output in scenario 2 suggested a more extensive output than only the direct impacts of shutting down all Norwegian aluminium smelters.

Regarding the reliability of these results, some points are worth mentioning. The reader should be aware that the main focus of this study has been to develop a model based on a set of MRIO tables, hybridize this with more detailed aluminium process data and show the potential of combining this with the input-output methodology and software tools as a framework for assessing environmental impacts of aluminium production based on production, trade or consumption. As such, the main focus has not been on data collection and validation, but on model development. Furthermore, the scenarios were intentionally designed as simple as possible to facilitate the appreciation of the model's inherent mechanisms. Nevertheless, the overall data quality should be high, as the MRIO tables are generally constructed from official make and use tables from the EU, which follow the same framework assumed in the input-output methodology.

As explained in chapter 4, the flow matrix in the MRIO was constructed by patching together domestic flow and import matrices for each region. The domestic flow matrices were directly adapted from the ESA tables and as such should be very reliable. As for the inter-regional trade flow matrices, these were based on aggregated import matrices for each region that were split up according to trade share patterns from the somewhat older GTAP database. For the ROW regions, complete trade flow matrices were adapted from the GTAP databases. Total import flows for the European regions should be correct, although trade shares may be slightly off. All in all, the flow matrix Z as well as the final demand Y should be fairly accurate.

The stressor matrix S was constructed from ESA emission data based on the NAMEA framework. Due to an apparent lack of co-ordinated reporting standards in the EU, there were large differences in the amount of emission statistics reported from each European region. Some countries omitted certain stressors, some reported emissions for highly aggregated economical sectors only, and some countries lacked emission data altogether. To fit the sector resolution chosen for this model (based on the EXIOPOL standard), these had to be disaggregated, and holes had to be filled using emission intensities from proxy countries. For this reason, there is some degree of uncertainty associated with the emissions data. As a general rule of thumb, the emissions of large countries are more accurate, as they were generally reported more completely and detailed than was the case for some smaller countries. The same way, CO_2 emissions were more thoroughly reported on the whole than less "common" substances such as NMVOC and SO_x, data of which the reader would be well-advised to exercise caution when using. Because of the large amounts of data, computer algorithms were produced for the task of disaggregating and approximating emissions. Consequently, some values may exist that are far off, possibly producing unlikely results such as the emissions related to Italian aluminium production calculated by this model. The emission totals have, however, been compared with external data when substantial approximations have been made, and adjusted accordingly. The emission data on a large scale should hence be fairly accurate, even if individual sector emissions may be wrong.

The adjustments made to the foreground sectors' flows were, apart from emissions and reciprocal flows, mainly related to inputs of electricity and transport, which were assumed to be considerably higher than those of the average "basic metals". As for transport, the European smelters were assumed to get their alumina from South and North America, which should be a reasonable approximation. The electricity inputs have some inherent uncertainty, especially concerning electricity prices, whose representative values were hard to estimate because of large specters of regional price differentiation and tax regimes. The foreground system's reciprocal flows and its specific emissions data were based on Steen-Olsen (2008), a study which in turn used mostly IAI and EAA data, and should as such be reliable. This analysis ran future simulations based on the assumption of fixed technologies, both concerning aluminium smelting and electricity production. The life cycle inventories used in the foreground system were adapted from the IAI inventories, which represented an average of the global smelters in 2000. This includes a significant share of Söderberg smelters, which are generally more emission intensive than prebake smelters. However, the Söderberg smelters are in fact being phased out, and virtually all new smelters today are prebake smelters — hence the aluminium production technology will in fact probably be somewhat different by 2030 than what was assumed in this study.

Also, the future simulation approach applied in this study, scaling the final demand (consumption) according to projected GDP increases for each region, is not necessarily a flawless approach. For comments on this issue, see Guisan (2001).

The model's ability to represent the global aluminium industry and its environmental repercussion in the base year 2000 was assessed by comparing specific emissions obtained from the model with corresponding results found in other studies. By applying a final demand of one unit of primary aluminium from a certain region to the model, one is able to investigate the model's representation of the resulting total flows and emissions — that is, the total cradle-to-gate impacts of producing that unit of primary aluminium. This corresponds to the result one would find by performing an ordinary life cycle assessment of one unit of aluminium.

As laid out in section 5.1, the total cradle-to-gate GWP and AP per ton of primary aluminium from the Norwegian aluminium sector were 8.46 tons CO_2-eq and 50.4 kg SO_2-eq. These were both only 5-10% off the analogous results found in the process-based LCA by Steen-Olsen (2008), which were calculated as 8.92 tons CO_2-eq and 46.2 kg SO_2-eq, respectively. Recall, however, that Bergsdal *et al.* (2004) found a GWP of 12.7 tons CO_2-eq per ton aluminium for an average smelter, which is significantly lower than the trends presented in table 5.2 of the present report.

Tan and Khoo (2005) found the corresponding impacts from aluminium smelting in Australia to be 18.3 tons CO_2-eq and 90.6 kg SO_2-eq. As shown in table 5.2, the present model results for the aggregate "Oceania" region were 21.3 tons CO_2-eq and 136.2 kg SO_2-eq. This is quite a lot higher concerning AP, more than 50%. GWP results agree more, but the results presented here are still considerably higher. This indicates that the results for the ROW regions may not be as accurate as for the EU23 regions, and they should as such be used with some caution.

With the present technology for producing primary aluminium, specific GHG and AP contributing emissions will invariably be high. This study as well as comparable studies all stress the importance of electricity production as a contributor to such emissions for the aluminium industry. Considering the large share of fossil fuels used as the source for electricity production today, a share that will probably remain quite high for many years to come, the cradle-to-gate emissions found in the present study are not likely to show dramatic decrease anytime soon.

The Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report in 2007. The contribution from Working Group III deals with options for climate change mitigation, devoting a lot of attention to emissions from industries (IPCC, 2007). They estimate a 15-25% mitigation potential for GHG emissions from the aluminium sector. The

IPCC identifies PFC emission control as the GHG source with the highest potential for impending reduction. Steps are being taken by the industry to achieve this, in fact the International Aluminium Institute has presented ambitions that its members should reduce their specific PFC emissions by 80% by 2010 compared to 1990 levels (IAI, 2007a). Although this was a voluntary objective, the IAI reports that this target was actually met and significantly exceeded as early as 2006, when these emissions were estimated to levels 86% less than the 1990 levels. In fact, the aluminium industry (as well as other industries) as a whole are generally placing increasing emphasis on sustainable production. For this reason, studies such as the present is increasingly sought after, as the environmentally extended input-output methodology is able to present overviews of any industry, highlighting important product flow patterns as well as their resulting direct and indirect emissions. Presently, few studies exist, mostly due to the large amounts of data needed — data that is commonly non-existent, requiring large degrees of estimates and approximation. However, with extensive databases such as the EXIOPOL project under way, and coordinated efforts by industry sectors to collect and organize data, as is currently the case for the aluminium industry (IAI, 2007b; EAA, 2008), this could well be changing.

The analyses performed in this study showed the importance of electricity when it comes to the environmental impacts of primary aluminium production. As such, the potential for large environmental gains quite possibly is found in technology improvement. Most importantly, a global shift towards more renewable energy would imply significant life cycle emission reductions for aluminium production. The most important GHG emission reduction efforts from the aluminium industry itself would be to improve the Hall-Héroult process, or even introduce a completely different way of producing aluminium. The carbothermic reduction (CTR) (ref. Thundal (1991); Warner (2008)) process or the inert anode technology (ref. The Aluminum Association (2003)) both show promising potentials as new smelting technologies, however neither is commercially viable at this time.

6.1 Conclusion and further work

The importance of aluminium in areas such as construction, transport, packaging, and so on has grown vastly over the last few decades. From its position as a rare, expensive metal reserved for the well-to-do only a century or so ago, it is currently being produced in quantities only exceeded by steel when it comes to metals. Lately, however, concerns have been raised about the relatively high emissions and energy requirements of the primary aluminium production process.

As shown in this study, the global primary aluminium industry is a relatively large consumer of energy and emitter of greenhouse gases, emissions that will keep growing rapidly with the projected demand development, unless technology improvements are made. By applying input-output methodology, the model showed the global emission structure of the present aluminium industry and highlighted the problem of geographical problem shifting if European aluminium companies were to move all new capacity investments to China, as was assumed in the model scenarios 1 and 2. As demands will grow regardless of the location of production, the result will be higher import requirements. The facts that aluminium smelting requires large amounts of electricity and that this is generally coal based in China would imply higher resulting emissions of greenhouse gases, and especially of the main contributors to acidification, SO_x and NO_x.

As climate change concerns grow and GHG emission caps are tightened, the issue of allocating emissions and track their underlying causes becomes vital. The European Union Emission Trading System (EU ETS) commenced operation in 2005, and is supposed to include more and more industries. Although this will indisputably spur emission reduction efforts by the affected European industries, one could assume that it would also make low-cost countries with no plans to introduce such a system more attractive locations for new capacity. The effects of such a development could be negative for the European economy, and lead to a more emission intensive aluminium sector overall, as suggested by the results of the scenario analyses. Consequently, it is of importance that an effort such as this has wide international support, and that other regions follow suit.

As mentioned earlier, the aluminium production technology was assumed to be static over the coming decades. This should be an area of focus in further studies, that should assess the potential for introducing new technologies and the implications of this. Regarding total life cycle emissions, this study has been limited in that it focused only on the upstream (cradle-to-gate) product flows and environmental impacts related to primary aluminium. Future studies should also address the downstream flows, i.e. where the aluminium goes, what it is used for, how it is disposed of — and the associated environmental impacts. Following this reasoning, as this study only focused on primary aluminium, such an extension should also include detailed models of aluminium recycling patterns, as recycling will undoubtedly be a very important issue in the years to come.

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Appendix A

Definition of Economical Sectors Assumed in the Model

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

1. Agriculture, hunting and related service activities (01),
2. Forestry, logging and related service activities (02),
3. Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05),
4. Mining of coal and lignite; extraction of peat (10),
5. Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying (11),
6. Mining of uranium and thorium ores (12),
7. Mining of metal ores (13),
8. Other mining and quarrying (14),
9. Manufacture of food products and beverages (15),
10. Manufacture of tobacco products (16),

11. Manufacture of textiles (17),
12. Manufacture of wearing apparel; dressing and dyeing of fur (18),
13. Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19),
14. Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20),
15. Manufacture of pulp, paper and paper products (21),
16. Publishing, printing and reproduction of recorded media (22),
17. Manufacture of coke, refined petroleum products and nuclear fuels (23),
18. Manufacture of chemicals and chemical products (24),
19. Manufacture of rubber and plastic products (25),
20. Manufacture of other non-metallic mineral products (26),
21. Manufacture of basic metals (27),
22. Manufacture of fabricated metal products, except machinery and equipment (28),
23. Manufacture of machinery and equipment n.e.c. (29),
24. Manufacture of office machinery and computers (30),
25. Manufacture of electrical machinery and apparatus n.e.c. (31),
26. Manufacture of radio, television and communication equipment and apparatus (32),
27. Manufacture of medical, precision and optical instruments, watches and clocks (33),
28. Manufacture of motor vehicles, trailers and semi-trailers (34),
29. Manufacture of other transport equipment (35),
30. Manufacture of furniture; manufacturing n.e.c. (36),
31. Recycling (37),
32. Electricity from hard coal; gas, steam and hot water from coal,

33. Electricity from nuclear power,
34. Electricity from natural gas,
35. Electricity from petroleum and nec,
36. Electricity from hydro,
37. Electricity from wind,
38. Collection, purification and distribution of water (41),
39. Construction (45),
40. Sale, maintenance and repair of motor vehicles and motorcycles; retail sale services of automotive fuel (50),
41. Wholesale trade and commission trade, except of motor vehicles and motorcycles (51),
42. Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52),
43. Hotels and restaurants (55),
44. Land transport; transport via pipelines (60),
45. Water transport (61),
46. Air transport (62),
47. Supporting and auxiliary transport activities; activities of travel agencies (63),
48. Post and telecommunications (64),
49. Financial intermediation, except insurance and pension funding (65),
50. Insurance and pension funding, except compulsory social security (66),
51. Activities auxiliary to financial intermediation (67),
52. Real estate activities (70),
53. Renting of machinery and equipment without operator and of personal and household goods (71),
54. Computer and related activities (72),

55. Research and development (73),
56. Other business activities (74),
57. Public administration and defence; compulsory social security (75),
58. Education (80),
59. Health and social work (85),
60. Sewage and refuse disposal, sanitation and similar activities (90),
61. Activities of membership organisation n.e.c. (91),
62. Recreational, cultural and sporting activities (92),
63. Other service activities (93),
64. Private households with employed persons (95).

Appendix B

Aluminium Production Data, Year 2000

Global production statistics were obtained from the United Nations Industrial Commodity Statistics Database (United Nations, 2009b). Price estimates were obtained by combining these with aluminium export data from the United Nations Commodity Trade Statistics Database (United Nations, 2009a). Total outputs from the "basic metals" sector of each country were extracted from the model itself.

Region	Physical Al output	Export Price	Share of basic metals sector
Austria	158.1	1620.6	1.8%
Belgium	-	-	-
Czech Republic	40.0	1327.5	0.8%
Denmark	-	-	-
Estonia	-	-	-
Finland	-	-	-
France	700.9	1895.6	2.3%
Germany	403.5	1721.3	0.7%
Hungary	88.9	1820.9	4.7%
Ireland	-	-	-
Italy	757.3	1719.0	7.5%
Lithuania	-	-	-
Luxembourg	-	-	-
Malta	-	-	-
Netherlands	405.0	1686.0	3.7%
Norway	1280.3	1879.5	15.7%
Poland	11.8	1492.9	0.2%
Portugal	-	-	-
Slovakia	109.8	1885.5	4.3%
Slovenia	-	-	-
Spain	366.0	2065.0	2.6%
Sweden	35.0	1841.2	0.4%
United Kingdom	305.0	1780.4	1.3%
Oceania	2028.0	1799.6	38.9%
China	2989.2	1343.9	8.8%
Asia	5843.7	1343.9	8.5%
North America	6041.0	1790.3	8.2%
South America	1867.1	1812.2	15.0%
Rest of Europe	919.9	1166.0	5.3%
Middle East	665.3	1038.4	2.2%
Africa	1171.4	1457.5	9.5%

Table B.1: Data on the global aluminium industry assumed in the model simulations.

Appendix C

Electricity Mixes

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

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

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

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

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

Appendix D

Matlab Code

Below is the master script applied to construct and run the scenario simulations assumed in this study. For more details on the individual calculations steps performed in constructing the model, the reader is referred to the digital appendix, where the complete set of Matlab scripts written and used are included.

```
% Master script that includes all scripts used to prepare the matrices used
% in my Master thesis.
%
% Author: Kjartan Steen-Olsen
clear all
clc

% Starting timer:
t1 = clock;

%% Running preparatory scripts (generates basic A, L, s, v, and y):
% S_ESA
% Emissions_inserter
% disag_el_emissions
% MainKjartan
% new_s_el
load MainK_results
load frame
clear Z %Y

%% Test:
% test
```

```
%% Base scenario modeling:
scale_y
y_SB_vector = squeeze(sum(y_SB,2));
clear y_SB

for i=1:4
    x_SB(:,i) = inv(eye(size(A,1))-A)*y_SB_vector(:,i);
    x_SB(x_SB<1e-6) = 1e-6;
    Z_SB(:,:,i) = A*diag(x_SB(:,i));
    e(:,i) = s*x_SB(:,i);
    E_dir(:,i) = diag(s(2,:))*x_SB(:,i);
    E_Z = diag(s(2,:))*Z_SB(:,:,i);
    E_Z_f(1:2077,1:31*3,i) =...
        E_Z(:,[65:3*31+64]+(67-3)*floor([0:3*31-1]/3));
    clear E_Z
end

% Aluminium trade flows:
for n = 1:4
    for i = 1:31
        for j=1:31
            trade_BL(i,j,n) = sum(Z_SB(67*(i-1)+65,67*(j-1)+1:67*j,n))/...
                (newsectors_basis(1).price(i)/1000);
        end
    end
end

% clear A

%% Scenario 1/2: All new aluminium production in China (S2: NO Al --> 0):
AlC = 67*24+65;

sn = input('Please choose scenario 1 or 2: ');

% Calculating total increase in global Aluminium sales - in tons:
AluS = Z_SB(65:67:end,:,:);
for i=1:4
    AluS_ph(:,:,i) = inv(diag(newsectors_basis(1).price'/1e6))*AluS(:,:,i);
end
AluS_ph_tot = sum(AluS_ph);
```

```
for n=2:4
diffS_ph = squeeze(AluS_ph_tot(:,:,n) - AluS_ph_tot(:,:,1));
diffS = diffS_ph*newsectors_basis(1).price(25)/1e6;

Z_SC_n_temp = squeeze(Z_SB(:,:,n));
Z_SC_n_temp(65:67:end,:) = Z_SB(65:67:end,:,1);
Z_SC_n_temp(AlC,:) = Z_SC_n_temp(AlC,:) + diffS;
if sn == 2
    Z_SC_n_temp(1070,:) = Z_SB(1070,:,1)*((4-n)/3);
    Z_SC_n_temp(AlC,:) = Z_SC_n_temp(AlC,:) +...
        (Z_SB(1070,:,1)-Z_SC_n_temp(1070,:))/...
        newsectors_basis(1).price(16)*newsectors_basis(1).price(25);
    y_SB_vector(1070,n) = y_SB_vector(1070,1)*((4-n)/3);
    y_SB_vector(AlC,n) = y_SB_vector(AlC,n) +...
        (y_SB_vector(1070,1)-y_SB_vector(1070,n))/...
        newsectors_basis(1).price(16)*newsectors_basis(1).price(25);
end

Z_SC_n_temp(Z_SC_n_temp<0)=0;
A_SC = Z_SC_n_temp*inv(diag(x_SB(:,n)));
x_SC(:,n) = inv(eye(size(A_SC,1))-A_SC)*y_SB_vector(:,n);
x_SC(x_SC<1e-6) = 1e-6;
Z_SC_n = A_SC*diag(x_SC(:,n));

% Trade flows:
for i = 1:31
    for j = 1:31
        trade_SC(i,j,n) = sum(Z_SC_n(67*(i-1)+65,67*(j-1)+1:67*j))/...
            (newsectors_basis(1).price(i)/1000);
    end
end

% Emissions in Scenario 1:
E_SC_pu_fd = diag(s(2,:))*inv(eye(size(A_SC,1))-A_SC);
E_SC_pu_fd_f(:,:,n) =...
    E_SC_pu_fd(:,[65:3*31+64]+(67-3)*floor([0:3*31-1]/3));
e_SC(:,n) = s*x_SC(:,n);
E_SC_dir(:,n) = diag(s(2,:))*x_SC(:,n);
E_SC_Z_n = diag(s(2,:))*Z_SC_n;
E_SC_Z_f(1:2077,1:31*3,n) =...
```

```
    E_SC_Z_n(:,[65:3*31+64]+(67-3)*floor([0:3*31-1]/3));
clear diff* n Z_SC_n_temp E_SC_Z_n E_SC_pu_fd %Z_SC_n A_SC
end
E_SC_dir(:,1) = diag(s(2,:))*x_SB(:,1);
e_SC(:,1)=e(:,1);
```