NTNU – Trondheim
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Sectoral Model of the Cement Industry Using Input-Output Analysis

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“We may almost say of him [Joseph Aspdin, inventor of Portland cement] what the epitaph in St. Paul’s Cathedral says of Sir Christopher Wren: ‘If you seek his monument, look around’.”

-Anonymous

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MASTER THESIS

for

Sarah Lasselle

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Environmental Assessment of Scenarios for CCS Deployment in the European Cement Industry

Miljøevaluering av scenarioer for implementering av CCS i den europeiske sementindustrien

Background
Cement production is the second most CO_2 intensive industrial process. High CO_2 emissions in this sector are both due to large energy requirements and emissions from calcination of calcium carbonate (limestone) which is the raw material for cement production. Carbon capture and storage (CCS) technology, which is based on the concept of capturing CO_2 from large point sources and sequestering it away from the atmosphere, can therefore also be applied in conjunction with the cement industry. This would result in significant reduction in global warming (GWP), but will also have the environmental impacts inherent to a CCS system as presented in several studies.

Aim
This work aims to assess the environmental performance of CCS deployment scenarios for the European cement industry. The secondary objective is to assess how CCS in this sector has repercussions across other sectors and products; of particular interest are the impacts of the construction sector(s).

The analysis should include following elements:

1. Improvement of existing process LCA inventories for cement production with CCS.
2. Hybridization of process LCA inventories.
3. Development of scenarios of CCS deployment in the European cement industry.
4. Development of an environmental input-output model for scenario assessment.
5. Implementation of scenarios.
6. Analysis and discussion.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 1 February 2013

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Summary

This study assesses the effect CCS employment on the global warming impact of the European cement industry using Multi-Regional Input-Output Analysis.

For the cement sectors of the 28 European countries studied, technology and cohort distributions were established, thermal efficiency fuel input data were collected, and the capacity turnover and evolution of CO_2 emissions from cement production of each country were determined. An economic life cycle inventory of CCS implementation for cement was established, and a cradle-to-gate assessment of the cement production with and without CCS implementation was performed using the EXIOBASE multi-regional input-output model for the years 2013, 2030, and 2050.

The results of the analysis show that the implementation of CCS in the European cement industry leads to an increase in the emissions embodied in cement demand for Europe as a whole compared to a scenario where CCS is not used. However, the results of global warming impact due to cement demand vary from country. This illustrates the variations in production technologies of different countries and the importance quantifying emissions embodied in trade flows of goods throughout the world economy when calculating environmental impact.

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Sarah Lasselle

Trondheim, Norway
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Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Awareness of the dangers of climate change has put increasing pressure on industries to develop sustainable practices using low-carbon technologies. Projections indicate that without significant technological and societal changes, the level of carbon dioxide (CO_2) in the atmosphere will be over 800 ppm by the end of the century (Huntzinger and Eatmon 2009). One industry which is particularly important in the global battle against climate change is the cement industry. After water, concrete is the second most consumed commodity per volume annually by society. Cement is the binding component in concrete, giving the substance its strength.

The main constituent of cement is clinker, a substance made of hydraulically active calcium silicate materials. Clinker is produced by burning limestone and other materials at high temperatures in a kiln (Oss and Padovani 2002). The calcination of limestone, which releases CO_2, and the high heat of reaction make clinker production, and thus cement production, an energy- and emissions-intensive process. Nearly all of the direct emissions of CO_2 from cement manufacture are from clinker production. Because of its high demand and carbon intensive production process, cement manufacture is currently responsible for 5% of man-made CO_2 emissions (Worrell, Price et al. 2001).

To halt increasing global warming caused by CO_2 emissions, the IPCC has set a goal of reducing the CO_2 emissions of the cement sector by 50% of 2006 levels by 2050 (Barcelo and Kline 2012) in order to p. The commission has identified four ways of reducing CO_2 emissions during cement production: increasing thermal and electrical efficiency, increasing use of alternative fuels, substitution of clinker or reduction of clinker factor, and the use of carbon capture and storage (CCS) (IEA-WBCSD 2009).

While the first and second measures simply constitute a reduction of energy and fossil fuel use, CCS has a significant material and energy requirement. In order to quantify the environmental impact of cement production with and without CCS, it is necessary to perform a cradle-to-gate analysis of cement production with and without CCS. Additionally, for CCS to be a viable strategy for the cement industry to reduce its emissions by 50% by 2050, it is necessary to determine at what rate, and to what extent CCS must be employed in order to meet this goal.

1.1.1 Why Multi-regional input-output analysis?

A methodology commonly used to assess the impacts of a product's entire life cycle is Life Cycle Assessment (LCA). LCA is a technique which evaluates the environmental performance of a process or system by compiling the material and energy inputs, evaluating the outputs and emissions, and quantifying the environmental impacts (ISO 2006). Cradle-to-gate assessments refer to the modeling of the entire production process, up to when the product is ready at the factory gate. This technique is useful for quantifying the direct and indirect environmental impacts of a single unit product and comparing the impacts of variations of similar products.

Input-output analysis (IOA) is an appropriate tool for quantifying the direct and indirect environmental impact of industrial processes because it takes into account the entire life cycle of production. IOA differs from LCA in that it is based on the economic output of production sectors and their aggregate emissions. The life cycle inventories used in IOA are therefore economic inputs. As such, impact assessment using IOA includes impacts of the entire upstream processes, including impacts due to service sectors, which are difficult to quantify using physical inventories normally employed in life cycle assessment. Additionally, IO tables represent the entire economy of a region, and can show how overall performance of a region changes due to changes in specific sectors. A multi-regional input-output model represents the production technologies of each region, as well as the flow of goods from each region to satisfy the production demands of other regions.

While the IPCC's roadmap focuses on CO_2 emission reduction goals for individual sectors in order to achieve overall emissions goals, little is known about how emissions reduction of individual sectors will affect the emissions of the entire economy. This report therefore employs a multi-regional input-output model to determine how changes in the cement industry in each European country can achieve emissions reduction goals for the cement industry itself, and how changes to these sectors will affect the emissions of the entire world economy.

1.2 Literature Review

1.2.1 Cradle-to-grave analysis of cement manufacture

Due to the widespread use of cement and its importance in most built systems, many cradle-to-gate assessments of cement manufacture have been performed using LCA. A comparison of clinker production using an old production line, and a newly refurbished Best Available Technique (BAT) production line in a Spanish cement plant showed that direct CO_2 emissions of clinker production (the source of direct CO_2 emissions in cement production) were reduced by 4%, resulting in 0.84 t CO_2/t clinker, and that the total impact to global warming potential (GWP) per kg clinker was reduced from 987 g CO_2-eq to 938 g CO_2 due to the reduced fuel and electricity inputs of the more efficient production line (Valderrama, Granados et al. 2012).

A study employing LCA to evaluate cement manufactured in France found that the GWP potential of 1 kg of cement consisting of 95% clinker to be 906 g CO_2-eq (Chen, Habert et al. 2010). Conversely, the French Technical Association of the Hydraulic Binder Industry (ATILH) found the life cycle GWP impact of cement consisting of 95% clinker to be 899 g CO_2-eq per kg cement. The study also compared emissions per kg of cement using their own calculated direct emissions, data for average direct emissions given by the ATILH, and data for direct emissions from specific cement plants. The study concluded that significant variations in direct CO_2 emissions of cement production expressed in the different available sources were due to variations in plant technology. More specifically the type of cement kiln result in changes in GWP by 20%, given a constant clinker content.

Many of the life cycle assessments performed on cement production conclude that emissions data is highly variable and that finding reliable data is difficult (Gartner 2004). In their analysis of available life cycle inventories of cement in the European Union (EU), Josa et al. (2004) concluded that the average emissions values available tend to agree with individual plant data, but that more information is needed for plants in less technologically advanced countries, which represent the upper bounds of these emissions, to better compare production of cement in different regions (Josa, Aguado et al. 2004).

The emissions of cement production will vary not only by region, but also over time, as older, less efficient kilns become obsolete and are replaced with efficient kilns. N. Pardo et al. (2011) performed a study which estimates the changing energy efficiency of the European cement industry based on the technology distribution of kiln types in 2002, and modeling the turnover of kilns from 2002 to 2030. This study was performed using kiln technology distribution for Europe as a whole, and showed a reduction in direct emissions from 0.86 kg CO_2/kg clinker in 2010 to 0.85 kg CO_2/kg clinker by 2030 (Pardo, Moya et al. 2011). This shows while kiln technology is important to determine the CO_2 emissions of an individual plant, the rate at which kiln technology evolves in the EU will affect the rate at which CO_2 emissions per unit of cement are reduced.

1.2.2 Analysis of CCS in conjunction with cement manufacture

Several studies have been performed which evaluate the life cycle environmental performance of CCS in the power sector. Techno-economic assessments of CCS used in the cement industry have been also been conducted, but there are no published life cycle assessments of cement production used with CCS.

CCS is an option which seems most attractive for the power generation industry, because it has the potential to reduce the carbon footprint of the energy mix used in an economy. Several life cycle assessments, and technical economic studies have been performed for CCS in the power industry. Environmental assessments show that CCS is an effective means of reducing greenhouse gas (GHG) emissions, but that there are environmental tradeoffs, mostly related to toxicity impacts (Singh 2011). The increased toxicity impacts of power production with CCS are due to the leakages of chemicals necessary for CCS into the environment.

CCS in the cement industry is seldom employed because of the energy and economic cost associated with this method (Gough 2008). Recent studies have shown that costs of CCS for industrial processes such as cement manufacture can range from \$20-\$75 per ton CO_2 avoided (Farla, Hendriks et al. 1995; Hassan 2005). For a cement plant producing 1,500,000 tons per year with emissions of 1.02 kilo tons of CO_2, (Chen, Habert et al. 2010) this corresponds to a cost of up to \$76,500 per year.

As reported by Naranjo et al. (2011) in their review of CCS possibilities for the cement industry, pre-combustion CCS does not capture CO_2 emissions from the chemical reaction of cement production, only the emissions from fuel combustion. Additionally, CCS with oxy-fuel combustion (combustion involving the use of pure oxygen) requires major retrofitting, making post-combustion CCS technologies the most feasible CCS method for use in the cement industry (Naranjo, Brownlow et al. 2011). In their comparative assessment of CO2 capture technologies for carbon intensive industries, Kuramochi et al. (2012) concluded that for the short and medium term, post-combustion technologies using monoethanolamine would be the only feasible technology, with a cost of 70€/tCO_2 avoided and an avoidance rate of 0.6 t CO_2/t clinker (Kuramochi, Ramírez et al. 2012).

The cement industry itself is also in the process of testing the feasibility of CCS in conjunction with cement production. The European Cement Research Academy (ECRA) has conducted preliminary technological and economic assessments of post-combustion and oxy-fuel CCS technologies. Their conclusion is that CCS technology developed specifically for cement use is not mature enough for use in the industry, and that CCS is currently too expensive for widespread use (Chandelle 2010). Despite these results, ECRA is still conducting several studies, including one in association with the Spanish government, to test CCS technology at cement plants. Results from this study are not yet available but its implementation illustrates that the industry is actively exploring this technology as a means of emissions reduction.

1.3 Research Objectives

1.3.1 Knowledge gap

The studies involving CCS in conjunction with cement production show that both the scientific and industrial communities are interested in reducing the CO_2 emissions of cement. Currently, no assessments have been performed which illustrate the life cycle GWP of cement produced with CCS, i.e. no studies have quantified the direct and indirect GHG emissions of cement production with CCS per kg cement.

The life cycle assessments of cement production in the studies mentioned above are based on physical life cycle assessment inventories. Specifically, they are based on country- or plant-specific data to calculate direct emissions from cement production, while the indirect emissions are based on the Ecoinvent database (Chen, Habert et al. 2010; Valderrama, Granados et al. 2012). Ecoinvent is a life cycle inventory database by the Swiss Centre for Life Cycle Inventories, a compilation of more than 2500 background processes mostly based on European and Swiss data (Frischknecht and Rebitzer 2005). It contains a life cycle inventory for cement, but this inventory is based only based on the Swiss cement industry and the thermal efficiency and fuel inputs therein (Kellenberger, Althaus et al. 2007). Currently, there exists no comprehensive database of varying fuel inputs and thermal efficiencies of cement production for each country.

The Ecoinvent database does not illustrate how changes in the cement sector of one or several countries over time will affect the GWP of the cement sector in total. An LCA based on a physical inventory will show the environmental impacts per unit production, but it does not contain the impacts of services necessary for production, nor does it show how changes in one sector will affect the emissions of the entire economy.

Regarding the goals sector based goals that are set by the IPCC, there is no analysis of changes in implemented to reduce the GHG emissions of one sector affect the emissions of other sectors. Implementing CCS in cement, for example, can decrease the emissions of cement, but may lead to an increase in the emissions of other sectors. When combatting a global problem such as global warming, it is important to determine how changes in one part of the world economy will affect the performance of the global economy as a whole.

1.3.2 Goal of analysis

The objectives of this analysis are to perform a cradle-to-gate analysis of cement production in Europe using a multi-regional input-output analysis, to generate higher resolution of the impacts of cement production in each country in Europe, to determine the rate of change of global warming impacts of cement production with and without the implementation of CCS. The countries in Europe to be analyzed are the EU-27 countries, except Malta which does not have a cement industry, plus Norway and Switzerland. (Further mention of the EU countries in this report refers to these 28 countries.)

To generate a clearer picture of the impacts of cement production in each country, country specific data for thermal efficiency and fuel inputs will be collected. To determine the rate of change of global warming impact of cement production, ages of plants in each European country will be established, and the rate at which plants are replaced will be calculated. This will show how the thermal efficiency and CO_2 emissions of cement production vary in each country, and over time, with and without CCS implementation.

An economic inventory for CCS implementation in a given plant will be established, and the changes in emissions for each plant will be calculated. The result will be a refined set of inputs and emissions factors to the cement industry for each country. The inputs will correspond to the fuel needs of cement domestic production, as well as the other physical and economic inputs necessary to employ CCS in the country.

This refined set of inputs will then be inserted into a multi-regional input-output table (MRIOT) which will then be used to calculate the total global warming impact of cement production in each country, with and without CCS.

2 Methodology

2.1 Methodological background: Input-Output Analysis

The aim of this study is to quantify the cradle-to-gate impacts of cement production in the EU. To do so, a multi-regional input-output model is employed. LCA methodology is also referred to when comparing the physical results of the analysis to other studies. The rudimentary framework for IOA and environmental impact assessment is explained in this section. Further information on the basic mathematics of IOA and LCA can be found in the texts *Input-Output Analysis: Foundations and Extension* (Miller and Blair 1985) and *Methodological Essentials of Life Cycle Assessment* (Strømman 2010). Information regarding the quantification of environmental impacts due to environmental stressors can be found in *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint leve*l (Goedkoop, Heijungs et al. 2009). In this analysis, standard variable names outlined in these texts are used.

IOA is an analytical framework whose purpose is to analyze the interdependence of industries in an economy. This inter-industry dependency is illustrated by the direct requirements matrix, *A*, is a square matrix in which each column represents a sector. The requirements from the other sectors which are necessary for one unit of output from a given sector are represented in the rows of the column.

For an exogenous demand, *y*, a vector of demand for consumption of each sector in the economy, the output of each sector, *x*, can be determined with the following identity:

$$x = Ax + y$$

Here, *Ax* is the intermediate demand and *y* is the exogenous demand. Solving the model for total output of each sector results in the following:

$$x = (I - A)^{-1}y = Ly$$

The $(I\text{-}A)^{-1}$, or *L*, matrix represents the industry output requirements per unit final demand. The above identities allow IO practitioners to determine the final outputs from each industry necessary to satisfy consumer demand. When environmental extensions are applied, the analysis is useful for quantifying environmental impacts of a given demand. The environmental extensions matrix, otherwise known as the stressor matrix, *S*, shows environmental impact per unit output of a sector. In the case of this analysis, environmental extensions are greenhouse gas emissions: CO_2, CH_4 and N_2O.

The total emissions, e, actuated in order to satisfy the final demand, y, are quantified as follows:

$$e = Sx = S(I - A)^{-1}y$$

Quantifying the total impact of the environmental stressors is performed using the characterization matrix, C, which quantifies the environmental impacts per unit stressor. In this analysis, only the environmental impact category of global warming potential (GWP) is assessed. The characterization matrix contains the kg CO_2-eq, the unit for measuring GWP, per kg GHG emission. The total environmental impact, *d*, of an exogenous demand, *y*, is quantified as follows:

$$d = CSx$$

2.1.1 Multi-regional Input-output analysis

The above equations illustrate the rudimentary framework of IOA, but the parameters represent a single economy. In reality, the economy of any given region will import goods to satisfy intermediate and consumption demand, as well as export goods to satisfy the intermediate and consumption demand of other countries. Taking this into account, the basic input-output balance for a given country can be represented as the following (Peters and Hertwich 2009):

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

Here, A^d and A^{im} represent the industry requirements matrices of domestically produced products and imported products, per unit output, respectively. y^d represents final demand of products produced and consumed domestically, y^x represents products produced domestically but consumed in foreign regions, y^{im} is the final demand of imports, and *m* represents products consumed for final and intermediate demand produced outside the region.

The domestic output for a given country is therefore:

$$x = (I - A^d)^{-1}(y^d + y^{ex})$$

Additionally, the environmental impacts embodied in domestic production are:

$$d^d = CS(I - A^d)^{-1}(y^d + y^{ex})$$

For global environmental concerns, such as global warming, it is important to understand how the consumption of goods produced domestically and abroad contribute to the total environmental impact (Peters and Hertwich 2009). If a country consumes a given amount of certain commodity, and half of the consumption is from domestic production, and half of the consumption is from imports, the emissions embodied in consumption will vary depending on how the production technologies of the domestic and exporting economies differ.

Multi-regional input-output analysis (MRIOA) extends the IOA model by giving each sector of each region its own row and column in the requirements matrix. For an IO model with 3 regions, the MRIO system is illustrated below:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix}$$

Here, A_{ij} represents the requirements matrix of goods produced in country *i* per unit output of goods produced in country *j*. y_{ij} represents the demand vector of country *j* for goods produced in country *i*. Summing the rows of the *y* matrix gives the total demand from each sector of each country. A more detailed derivation of the theoretical framework can be viewed in Peters and Hertwich, 2004.

There are several advantages to including multiple regions in the IO model. The first is that it better represents production processes and interregional trade so that the impacts of production processes and energy mixes that vary from country to country will be included in the calculation of total environmental impact of actuated to satisfy the consumption demands of a country. The second advantage is that such a model will also quantify trade feedback loops. A trade feedback loop occurs when trade takes place between two or more countries. For example, demand in country A for a commodity produced in country B will instigate an intermediate demand of commodities produced in country A. The commodities produced in country A, to satisfy the intermediate demand of B, will again instigate an intermediate demand of commodities produced in country B, and the loop continues. The MRIO model quantifies these feedback loops so that they are included in the calculation of the total output of each sector.

2.1.1.1 Applying the MRIO model to find impact of the cement sector

In the MRIO model, there are two ways to quantify the total global warming impact of the cement sector: using output (production) based impact allocation, or demand (consumption) based impact allocation. Production based allocation allocates the impact based on sector output. In this case, the global warming impact of the sector is calculated using the equation:

$$D_{sector} = CS\hat{x}$$

Here, D_{sector} is an impact matrix where each column represents each of sectors of individual regions. For example, if the economy in questions consists of 3 regions, each with 4 sectors, the D_{sector} matrix will contain 12 columns. x represents the output of each sector in each country, it will be a vector of 12 rows, and S represents the emissions per unit output of each sector of each country. In this analysis D_{sector} has only one row representing the GWP impact category. The values of the D_{sector} matrix represent the GWP impact due to *output* of each of the world's sectors. The total production based GWP impact of the European cement sectors using production based allocation is the therefore the sum total of the GWP impact from the cement sector of each European country.

The second means of quantifying the global warming impact of the cement sector is to allocate the impact based on sector demand. In this case, the global warming impact of the cement sector is calculated using the following equation:

$$D_{sector} = CSL\hat{y}$$

Here, the values of D_{sector} represents the impact of global warming due to the *demand* placed on each sector. y represents the exogenous demand for each sector of each country. While the *output*-based allocation shows how the direct emissions of the cement industry contribute to the total global warming impact of the economy. The *demand*-based allocation shows how the direct emissions of the cement industry and the emissions from the upstream processes of cement production contribute to the total global warming impact of the economy.

2.1.2 EXIOPOL Database

The quality of Input-Output analysis is dependent upon the quality of the Input-Output tables, which are usually compiled using data collected by national statistics offices. The IO framework used for this analysis is the EXIOPOL (A New Framework Using Externality Data and Input-Output Tools for Policy Analysis) database. EXIOPOL is an EU funded project which has created global, multiregional environmentally extended IO framework consisting of 43 countries, 129 sectors, 80 resources, and 40 emissions (Tukker, de Koning et al. 2013). The result is a harmonized, global Multi-Regional Environmentally Extended Input-Output Table (MRIOEET) with externalities (emissions factors) called EXIOBASE (EXIOPOL 2011).

This framework has been compiled using supply and use tables (SUT) and input-output tables from Eurostat and non-EU statistical offices. The final product is an IO framework which is a significant leap forward in the field of IOA because it takes interregional trade into account and contains a greatly extended list of environmental stressors. Most IO tables do not fully illustrate the relationships of global trade, partly because quantifying these relationships is data-intensive (Tukker, de Koning et al. 2013). The EXIOBASE framework however, contains full trade matrices which show which product from which country is exported to sectors of different countries to satisfy intermediate and final demand.

The EXIOBASE framework provides country-specific trade flows which can be used to perform an analysis showing how changes to the individual cement sectors of each country will affect total GHG emissions. In order to calculate how changes over time will affect the environmental performance of the economy, a time series of the EXIOBASE framework based on the International Energy Agency's (IEA) Baseline Scenario was employed.

This time series was compiled at the Programme for Industrial Ecology at the Norwegian University of Science and Technology. The IEA Baseline Scenario refers to a modeling framework which projects the development of technology, emissions, and energy mixes used in the world's regions from now until 2050. These scenarios explore how factors such as fossil fuel subsidies, research and development expenditure, and primary energy supply will develop until 2050. The purpose of the scenarios is to determine the best means of creating a low-carbon world economy. The baseline scenario refers to the "business as usual" case, where the current practices in the globe's energy sector are assumed to remain in place with little external political incentive to change (IEA 2008).

The time series of the EXIOBASE framework made for the baseline year, 2010, for 2030, and for 2050. It was assumed that the baseline year corresponds closely to the current economy in 2013. The global warming impacts due to changing cement industry were thus calculated for each of these years. The time series is made for the world's 9 regions, while the EXIOBASE format is made for 44 regions.

2.2 Workflow of analysis

In broad terms, the goals of the analysis were accomplished mapping the technology, age, thermal efficiency, and fuel inputs of all cement production in the EU, and determining a rate at which cement plants become obsolete and new ones are built. From this information, a time series of fuel inputs, energy efficiency, and greenhouse gas emissions per unit of cement production in each country was established. The inputs were inserted into the A and S matrices of the EXIOBASE time series, and the GWP impacts of cement production in the model years were calculated.

Table 1 lists the specific steps of the methodology, the necessary input data, the analytical goals of each step, and the sources for the necessary data.

Table 1: Methodological steps of analysis

Methodological step	Data inputs	Analytical outputs	Data sources
Map current use of kiln technology, fuel use, and kiln ages in EU	Individual plant data, for kiln type, fuel inputs, energy efficiency, and dates kilns were constructed. Country aggregated data for the largest producing countries. Capacity and production information for each country	Average thermal efficiency and fuel inputs per unit of cement in each country.	Publicly available information from over 80 cement plants, shown in Appendix A. Country aggregated data from the Cement Sustainability initiative (Klee, Hunziker et al. 2011), shown in Appendix B. USGS mineral yearbooks
Determine rate of cement plant capacity turnover in each country	Demand projections for cement based on per capita GDP (commodity intensity) Population projections GDP projections Historical consumption data for calibration Assumption for the thermal efficiency of new cement plants built after 2013	Projections of total capacity of cement plants in each country from 2013 to 2050 Future vintage distributions of the cement industry in each country Future kiln technology distribution of the cement industry in each country Future fuel input distributions and emissions factors of each country	GDP and population projections found in EU estimates (European Commission 2012; Eurostat 2013), shown in Appendix C. Commodity intensity curve for cement found in (Pardo, Moya et al. 2011), shown in Figure 2 New plant assumptions are based on GNR data and (Bauer and Hoenig 2010), outlined in section 2.4.8
Combine the 9x9 region EXIOBASE time series model, and the 44x44 country specific model to create a time and country-specific MRIO framework	The 44x44 country EXIOBASE IO framework The 9x9 region EXIOBASE IEA time series framework	Three 44x44 region MRIO tables for the years 2013, 2030, and 2050	(EXIOPOL 2011)

Determine necessary material and energy inputs per kg CO2 avoided when CCS is used	Life cycle cost assumptions of the CCS for the cement industry	Costs of material and energy inputs per unit CO2 avoided	Literature (Hassan 2005; Rubin and de Coninck 2005; Peeters, Faaij et al. 2007)
Convert fuel inputs and emissions factors per unit of physical cement to fuel costs and emissions per unit economic output of cement	Prices of fuels and cement Inflation rates Price valuation estimations	Cost of fuel and CO2 emissions per M€ output of cement	Prices, inflation, and price valuation can be found (Eurostat 2012)
Insert the calculated material, energy, and emissions information for cases where CCS is implemented and CCS is not implemented, into the three 44x44 country MRIO tables, calculate GWP	Cost of material and energy input determined by previous steps	The GWP potential of the cement industry in Europe.	

The following sections of the methodology chapter will describe the assumptions and execution of the above steps in more detail.

2.3 Process descriptions

2.3.1 The Cement Manufacturing Process

The cement manufacturing process consists of 4 basic steps: (BREF 2012)

1) Collecting raw materials
2) Preparation of raw mixture
3) Pyroprocessing (clinkering)
4) Cement manufacturing, grinding and packing of final product

Methods for completing the basic steps of cement manufacturing and the associated emissions and energy consumption will vary depending on the equipment and processes used in a particular plant. (BREF 2012; Valderrama, Granados et al. 2012) Various technological advances have been made in kiln, heating, and cooling technologies over the past decades, but a cement plant can have a lifetime of around 50 years, meaning that the technology used at present can vary greatly. (Kellenberger, Althaus et al. 2007) A description of best available techniques and commonly used technologies is provided in this section.

Collecting of raw materials includes mining and procuring limestone, calcareous marl, chalk, sand, clay and other materials. The raw mixture is ground in a mill, whose specific energy consumption varies depending on type. (BREF 2012) Examples of mills include ball mills, tube mills, and vertical and horizontal roller mills.

Solid fuels must also be ground and prepared for kiln feeding. In Europe, the most common fossil fuels used in cement manufacturing are petcoke and coal, but waste fuels are also frequently used.

During pyro processing, or clinkering, the raw meal is fed into a rotary kiln. There are six types of kiln technologies used in Europe today: dry process kilns with precalcination and preheating (PHPC), dry process kilns with preheating (PH), dry long process kilns (DL), semi dry kilns, semi wet kilns, and wet process kilns. In a dry kiln, raw meal is fed into the kiln as a fine, dry dust. Preheating is the process by which exhaust gas warms the raw meal before it enters the kiln and precalcination is a process where secondary fuel burning occurs in a special combustion chamber between the preheater and the rotary kiln. After precalcination, the raw meal is approximately 80% calcinated. This is the most efficient system because preheating and precalcination make use of waste heat from the exhaust to complete partially complete the chemical reactions necessary to make clinker. 5-6 cyclones are ideal for optimal heat exchange (BREF 2012). The standard for modern plants is a suspension preheater consisting of towered cyclones through which hot exhaust gas and raw material are fed (Oss and Padovani 2002). The process heat constitutes about 80% of the energy required in the manufacture process (Capros, Mantzos et al. 2008). The Table 2 shows the thermal energy requirements of the different kiln types, according to the European Commission's *Best Available Techniques for the cement and lime industry* and the IEA.

Table 2: Thermal efficiencies of kilns technologies

Process	Specific thermal energy (MJ/ton clinker) (BREF 2012)	Process	Specific thermal energy (MJ/ton clinker) (IEA-WBCSD 2009)
Dry process, multistage (3-6 stages) cyclone preheater and precalcining kilns	3000 - <4000	Dry process kilns with preheating and precalcining	3620
Dry process kilns with cyclone preheaters	3100 - 4200	Dry process kilns with preheating	3710
Dry process long kilns	Up to 5000	Dry process long kilns	3740
Semi-dry/semi-wet process	3300 - 5400	Semi-dry/semi-wet process	3950
Wet process long kilns	5000 - 6400	Wet process long kilns	5070

The remaining techniques: the semi-dry, semi-wet, and wet processes are older technologies, so a plant will switch to a dry process during an upgrade or an expansion. Wet technologies are sometimes necessary if the raw materials available in the area have a high moisture content. This is the case for a few producers in Belgium and Denmark. In the wet process, raw materials are ground with water to form a pumpable slurry. In the semi-dry process, this wet slurry is dewatered to form filter cakes which are extruded into pellets, then fed into a preheater or directly in to the rotary kiln. In the semi dry process, the dry meal is pelletized with water and fed into a grate preheater. (BREF 2012)

After raw meal is pyro-processed, the clinker must be cooled to ensure proper hydraulic properties. By blowing air over the clinker, heat can be transferred to the air which will be used for combustion in the main rotary kiln and precalciner. The two types of coolers are rotary and grate coolers, the most thermally efficient being the third generation grate coolers which emerged during the 2000s. (BREF 2012; Valderrama, Granados et al. 2012)

Once clinker has been produced and cooled, it is then ground with additives containing calcium sulfate, usually gypsum ($CaSO_4 \cdot H_2O$). (Oss and Padovani 2002) The resulting product is cement.

2.3.2 The Carbon, Capture and Storage Process

The post combustion CCS process consists of 4 basic steps: (Singh, Strømman et al. 2011)

1) Capture of CO_2
2) Transport of CO_2 to storage site
3) Injection of CO_2 to storage well
4) Monitoring and maintenance of storage site.

The type of carbon capture and storage system chosen for this model is a post-combustion, amine solvent-based system with a CO_2 removal efficiency of 90%. This kind of system is chosen because post-combustion CCS is easier to retrofit to an existing cement plant than other forms of CCS technology: pre-combustion and oxy-combustion. (Naranjo, Brownlow et al. 2011) An amine solvent-based system using monethanolamine (MEA) is chosen because this is the most commonly used solvent in post-combustion processes. (Wang, Lawal et al. 2011) 90% is the removal rate of the typical design rate of amine-based scrubbing systems. (Rochelle 2009)

The process of CO_2 capture is based on the reversible reaction between CO_2 with alkaline absorbents. The absorbents are generally amine in an aqueous solution. (Peeters, Faaij et al. 2007) In the capture process, the flue gas passes through a chemical absorption column, where the MEA absorbs the CO_2. The absorption occurs at approximately 40°C so the flue gas may need to be cooled. In a cement plant, this will depend on how much heat from the flue gas exhaust is used for preheating (Hassan 2005), and whether or not the flue gas has been through a desulphurization scrubber. (Kothandaraman 2010)

Flue gas enters the bottom of the absorption tower and the lean MEA solvent enters the absorption tower from the top. At this point, the lean solvent absorbs CO_2 present in the flue gas, and the now rich solvent exits the absorption tower from the bottom, flowing through a heat exchanger. The CO_2 rich solvent enters the stripper tower from the top and flows downward against the flow of warm vapors rising up from a reboiler. The increased temperature causes CO_2 to break its chemical bonds with the solvent. The effluent gas flowing out of the stripper is then a mixture of CO_2 and H_2O, which is cooled to separate out the water. The CO_2 rich stream is then compressed for transport. (Wangen 2012)

Because cement plants can have high emissions of SO_2 and NO_2 which react with MEA and degrade MEA, an MEA reclaimer which employs a strong alkali and to dissociate MEA may be necessary. This degradation also means that it is necessary to continuously add MEA to the system. (Kothandaraman 2010)

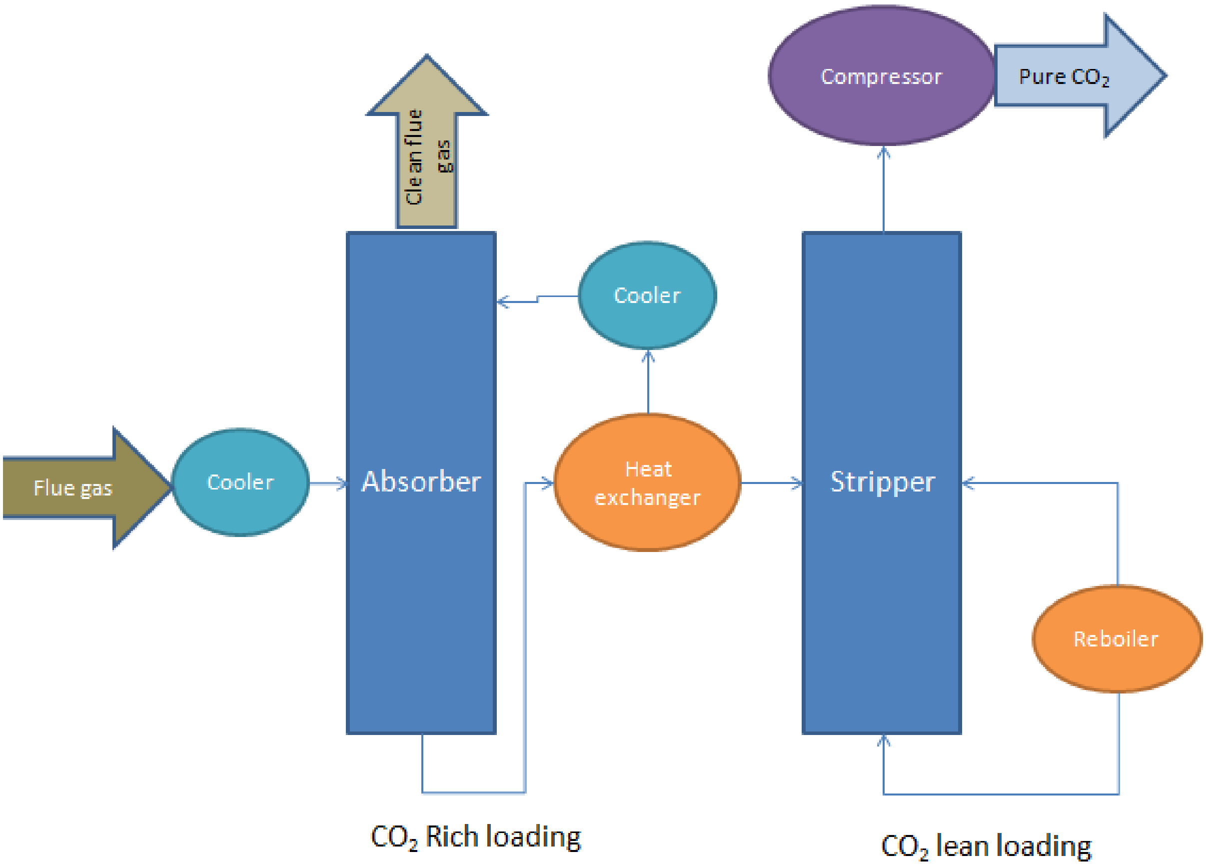

Figure 1 Schematic of post-combustion carbon capture process, adapted from (Peeters, Faaij et al. 2007)

The CO_2 is then pumped to a designated geological storage site. Storing the CO_2 in the site requires injection of the gas into a well, and a monitoring system. (Singh, Strømman et al. 2011)

The energy requirements of the capture part of the process are the thermal energy required for regeneration of the solvent; energy for driving the solvent pumps, flue gas blower, cooling water pumps; and energy for compressing the CO_2. (Singh, Strømman et al. 2011) In the transport and storage parts of the process, electricity to prevent a pressure drop in CO_2 as it travels through the pipeline to the storage site and for injecting the CO_2 into the storage well. (Singh, Strømman et al. 2011)

Of these energy requirements, the regeneration duty is the largest. Using some form of waste heat exchange to satisfy this requirement would therefore be ideal. A few studies outline the framework of reusing waste heat from clinker production to generate power, but these studies show that the amount of energy available in the form of waste heat is only a small fraction of the reboiler duty needed. (Karellas, Leontaritis et al. ; Wang, Dai et al. 2009) For the purpose of this report, waste heat recovery to satisfy the regeneration duty is therefore not considered feasible.

2.4 Model Development: Mapping the EU cement industry

2.4.1 Determining the demand of cement capacity

In order to determine the rate at which cement plants are built or remodeled in the European cement industry, it is necessary to determine the amount demand for cement in each country and how this demand will be satisfied over time. With this information, projections for necessary capacity over time can be made.

The demand for cement over time in each country was calculated by using the cement commodity-intensity curve given in (Pardo, Moya et al. 2011), shown in Figure 2. This curve shows the evolution of cement demand in kg per capita to GDP per capita. It illustrates a country's shift from agricultural to manufacturing economy, where the commodity demand increases quickly with increasing GDP per capita, and then a subsequent shift from an industrial to service-oriented economy, where the demand for cement drops with increasing GDP.

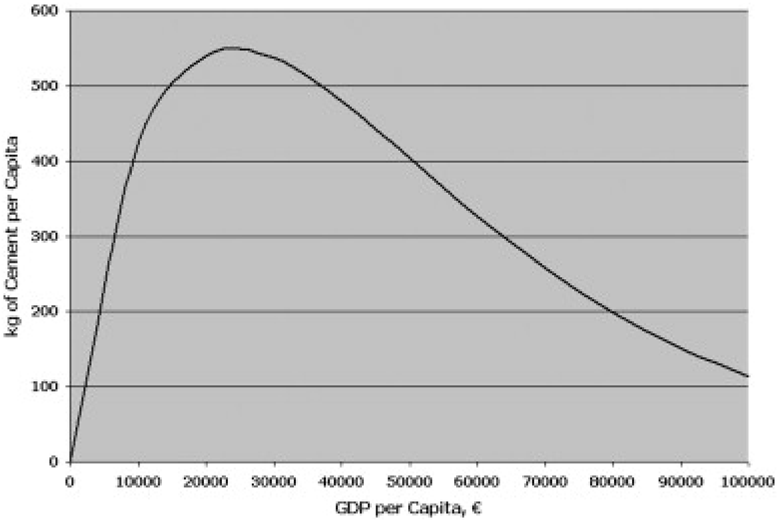

Figure 2: Commodity consumption curve for cement (Pardo, Moya et al. 2011)

2.4.1.1 Data calibration for determining rate of demand

The basis for calculating projections for the demand of cement over time was the commodity intensity curve shown in Figure 2. This curve provides the pattern for how cement consumption change over time, but it is not a perfect fit for every country given the variations in a country's climate, building styles, industry structure, etc. The curve therefore needed to be adjusted for each country. Historical values and projections for population and GDP for each country are available from Eurostat, and historical values for consumption from 2000-2010 are available from CEMBUREAU. The collected for this analysis is available in Appendix C.

The historical data for GDP per capita and cement consumption per capita was plotted and compared with the given curve. The difference between the expected cement consumption, based on GDP per capita and the given curve, and actual cement consumption for the years 2000-2010 was taken. The average relative difference between the expected and actual values was then used as a scaling factor. This scaling factor was used to scale the curve up or down when calculating the future demand for cement according to GDP per capita projections.

2.4.2 Determining rate of plant capacity turnover

To model the rate at which a country implemented new capacity, it was assumed that each country would have enough cement plant to capacity to cover domestic demand for cement. There are several reasons for this assumption. Demand for cement is satisfied domestically in the majority of cases because the necessary raw materials are available everywhere and because the costs of transportation of such a heavy commodity makes road transportation over 150 km economically unfeasible (Szabó, Hidalgo et al. 2006). There are a few exceptions to this in the EU. For example, Malta does not have any domestic production and Spain imports some clinker from non-EU sources (Ponssard and Walker 2008).

Some studies such as (Ponssard and Walker 2008) have considered the demand for cement production in various countries while taking into account trade between countries, the availability of a country to import cement via sea transportation, and cost of cement produced in various parts of the world. Ponssard and Walker's study indicates that a country may import cement or clinker if the price is low and sea transport is available, however a changing market situation in the exporting country, such as a spike in domestic demand, can affect the availability of cement for imports. It is therefore reasonable to assume that, given the uncertainty of the availability of imports, the cement industry in a given country will aim to have available capacity to satisfy domestic demand in the long term.

Calculating the rate at which kilns are replaced in each country reveals the rate at which thermal efficiency changes. The rate of capacity turnover was determined by a demand driven model. The demand corresponds to the demand for cement plant capacity in a country necessary to fulfill the domestic demand for cement. In the demand driven model, new capacity is added in a given year if the current capacity cannot satisfy the domestic demand for cement in that year.

When a plant reaches the end of its lifetime, its capacity is removed from the country's total capacity and it is replaced with a more thermally and electrically efficient PHPC plant if there is a need for capacity of the obsolete stock. The size of the new plant replacing the old plant is determined by the demand for capacity in the given year. The demand for plant capacity is the demand for cement in a given year divided by a capacity factor of 80%.

It was assumed that a cement plant becomes obsolete, and is removed from use after 50 years, the lifetime of a cement plant given in several sources (Kellenberger, Althaus et al. 2007; BREF 2012). It was also assumed that a plant is not taken out of commission unless it has reached the end of its lifetime. This assumption is based on the idea that cement plants exist in different areas of a country to satisfy local demand of cement. This means that if a country experiences a decrease in cement demand, it is assumed that the plants are spaced far enough apart that each plant will continue to operate part-time to supply cement to nearest markets, rather than assuming a country's cement demand is covered by a single plant.

2.4.3 Creating a dataset for the cement industries of EU countries

A bottom-up model of the European cement industry was created to estimate which portion of cement production in each country was created using each type of kiln technology, the approximate ages of the plants, and the fuel inputs. Much of the data used in the model is from the Cement Sustainability Initiative's *Getting the Numbers Right* (GNR) database (Klee, Hunziker et al. 2011). This database has information on kiln technology, fuel inputs, and electricity use for the EU-27 as a whole and for the largest cement producers in Europe: Austria, Czech Republic, France, Germany, Italy, Poland, Spain, and the United Kingdom (hence, GNR countries) for the years 1990, 2000, and 2005-2010. Individual information was then collected for each of the cement plants in the remaining countries of Europe from publicly available sources, mostly company websites and sustainability reports.

Renovation information was available for the years 2012, 2010, 2009, 2008, 2006, 2004, 2003, and 2001 in the technical publication *World Cement*, which publishes a "World Review" of renovations occurring at cement plants. A compilation of the information collected on the cement plants in each country is available in Appendix A.

2.4.3.1 Kiln technologies and thermal efficiencies

The first step in mapping each country's cement industry was to gather information on each plant's was the kiln technology use. The types of kiln were grouped into 5 groups: preheater with precalciner (PHPC), preheater without precalciner (PH), dry long or dry process unspecified (DL), semi-wet or semi-dry (SW/SD), and wet process kilns (W). Average thermal efficiency for each of these kiln technologies is given in the GNR database for the EU-27 and for the GNR countries.

The fraction of cement produced by each type of kiln for the EU-27 was available in the study (Pardo, Moya et al. 2011). The GNR databases contain data for the kiln technology distribution from the GNR countries, the average thermal energy efficiency of each kiln type in these countries and in the EU-27, the amount of clinker produced in each GNR country, and clinker factor of cement produced in the EU-27 and it GNR country. Clinker factor refers to the mass fraction of clinker per unit of cement.

The average thermal efficiency of each kind of kiln for the remaining EU countries was calculated by subtracting the contribution of each GNR country to the average kiln efficiency. These values for the average thermal efficiency for the kiln types were used for the non-GNR countries in the energy use calculations. The thermal efficiencies of the various kiln types are shown in Table 3.

Table 3: Thermal efficiencies of kiln types according to the GNR database

		PHPC		PH		DL		SD/SW		W	
Country	Fraction clinker produced in EU (%)	Fraction clinker produced (%)	Thermal efficiency (MJ/t clinker)	Fraction clinker produced (%)	Thermal efficiency (MJ/t clinker)	Fraction clinker produced (%)	Thermal efficiency (MJ/t clinker)	Fraction clinker produced (%)	Thermal efficiency (MJ/t clinker)	Fraction clinker produced (%)	Thermal efficiency (MJ/t clinker)
EU-27[1]	100	49.5	3620	30.5	3710	6	3740	10	3950	10	5070
Austria	9.9	60	3820	40	3790	-	-	-	-	-	-
Czech Republic[2]	1.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
France	10.3	36	3620	31	3790	-	-	33	3890	-	-
Germany[3]	17.5	33	3740	61	3840			6	NA	-	-
Italy	16.8	61	3630	12	4280	8	3630	19	3760	-	-
Poland	8.4	60	3850	40	3130	-	-	-	-	-	-
Spain	12.4	67	3490	33	3650	-	-	-	-	-	-
UK	5.1	100	3410	-	-	-	-	-	-	-	-
EU remaining[4]	18.1	36.4	3640	22.3	3669	16.5	3770	10.6	4164	14.2	5070

[1] The GNR database provides data on a plant-by-plant basis, some plants are listed as being “mixed” meaning they have several kilns of different technologies at the plant. The technologies at the mixed plants are unknown, so the technology distribution values for EU-27 are taken from from (Pardo, Moya et al. 2011), rather than the GNR database.

[2] Kiln distribution data was not available for the Czech Republic in the GNR database.

[3] In 2010, 14% of the German production was listed as being mixed. The technologies of mixed plants are unknown, so the technology distribution given for Germany in 2008 was used for this model.

[4] Calculated by removing the contribution of the GNR countries from the EU averages.

The technology distributions for the other countries were known or reasonably estimated based on publicly available plant information, shown in Appendix A.

The ratio of clinker production in a country was assumed to be the same as the ratio of integrated capacity. This means that if a PHPC plant constitutes 10% of a country's integrated plant capacity, that plant was assumed to contribute to 10% of the country's clinker production. Integrated plant capacity refers to a cement plant which has a clinker kiln, as opposed to a grinding plant. Kiln information was listed or could be inferred from the plant vintage in the majority of cases, the exceptions being some plants in Romania and Greece.

No individual plants were explicitly listed as using the dry long process, except for those in the GNR countries. If a plant was determined to use the dry process, but it was unknown whether or not preheating or precalcinaton was used, the kiln was assumed to be a dry long kiln. This assumption is based on the tendency of plants to actively proclaim a kiln's technology if it is new and efficient. Plants about whom little is known are likely older and less efficient because they do not want to advertise poor performance to the public.

2.4.4 Kiln cohorts

Based on the collected plant information and the "World Reviews" from *World Cement* showing renovation trends an average vintage year and standard deviation was established for each of the technologies, shown in Table 4. If the vintage (or cohort) of a plant was unknown, but the technology was the average vintage year for the technology was applied.

Table 4: Cohort assumptions for kiln technologies

Technology	Cohort range	Median cohort year	Standard deviation (years)
PHPC	1985-2001	1993	2.67
PH	1970-1995	1983	1.17
DL	1965-1980	1972	2.5
SW/SD	1960-1975	1967	2.5
W	1963-1969	1966	1

The cohorts of the newest plants in GNR countries were listed in the renovation information in the "World Reviews" from 2001-2012. For the remaining capacity in GNR countries, the capacity of each kiln type was assumed to be normally distributed over the above listed vintage ranges. This means that the capacity turnover for GNR countries will acts as a more continuous function, than that of the non-GNR countries because the plants of GNR countries are not modeled individually. However, this will still mimic the evolution kiln technology over time, so it was deemed a more reasonable solution than hunting down cohort data for the many plants in these large cement producing countries.

The established ranges do not mean that these technologies were never built outside of the established range. They are used as an estimation based on the plants for which cohort information is known.

2.4.4.1 Assumptions regarding grinding stations

A grinding station is a cement plant that does not produce clinker, but it grinds clinker that it receives from other sources. A grinding station does not affect a country's average thermal efficiency because it does not have a kiln, but it does add to the total cement production capacity in a country. In the capacity turnover model, it is assumed that a grinding station imports its clinker from domestic plants, so that the thermal energy embodied in clinker ground at the grinding station is the same as the average thermal energy requirements for integrated capacity in a country.

In countries with large cement sectors, this assumption is most likely correct, but countries with smaller cement sectors may import clinker. This means that thermal energy embodied in cement production of the country will differ from the average thermal efficiency of domestic clinker production. For the purposes of simplicity this fact was ignored in the capacity turnover model. Grinding station were included in the countries capacity to estimate the need for new plants, but they were assumed not to affect thermal efficiency of clinker production in a given country.

2.4.4.2 Assumptions regarding white cement

White cement differs from Portland cement or other kinds of composite cement because its white color requires more heat in during the clinkering process. Additionally, it requires a clinker factor of at least 90% (BREF 2012). White cement is thus more expensive, and the only difference between it and grey cement is its color, meaning that volume of white cement produced in Europe compared to grey is small (Ecofys 2009). It was therefore assumed that the future volume of white cement production would be so small that it would not affect the average thermal efficiency of new kilns.

2.4.5 Calibrating the model for kiln technologies and energy use

At this point, the kiln technologies and thermal efficiency values had been assigned to all of the plants in the non-GNR countries, and aggregated information for kiln technologies and thermal efficiency was available for the GNR countries. To verify the validity of the kiln technology and thermal efficiency assumptions, the total average thermal efficiency for the entire EU based on the model was compared to the average thermal efficiency for the EU given in the GNR database.

The amount of cement produced in each country was known from the USGS Mineral Yearbook of 2010. This information could be used to determine the fraction of the total European cement produced in each country. It was assumed that the relative fraction of total clinker produced in Europe by each country was the same as the fraction of total cement. Together with the fraction of clinker produced given by GNR countries, the USGS data was used to estimate the fraction of clinker produced by each country.

Table 5: Fraction of total EU clinker production from each country, based on GNR and USGS Mineral Yearbook; and fractions of clinker produced by different technologies, compiled using the GNR database and the information compiled in Appendix A

Country	Fraction of EU clinker production (%)	PHPC (%)	PH (%)	DL (%)	SD/SW (%)	W (%)	Unknown (%)
Austria	2.2	60	40	0	0	0	0
Belgium	3.9	68	0	0	0	32	0
Bulgaria	0.9	11.9	38.9	0	0	49.2	0
Cyprus	0.6	0	25.4	0	71.4	0	0
Czech Republic	1.5	48.9	17	34	0	0	0
Denmark	0.8	0	0	0	76.1	23.9	0
Estonia	0.2	0	0	0	0	100	0
Finland	0.6	100	0	0	0	0	0
France	10.3	36	31	0	33	0	0
Germany	17.5	33	61	0	6	0	0
Greece	4.3	11.9	15.5	0	4.8	0	67.9
Hungary	1.2	83.3	0	0	0	16.7	0
Ireland	1.1	60.4	28.6	11	0	0	0
Italy	16.8	61	12	8	15.2	0	0
Latvia	0.5	100	0	0	0	0	0
Lithuania	0.4	0	0	0	0	100	0
Luxembourg	0.5	0	100	0	0	0	0
Netherlands	1.3	0	100	0	0	0	0
Malta	0	0	0	0	0	0	0
Poland	8.4	60	40	0	0	0	0
Portugal	3.4	0	100	0	0	0	0
Romania	3.3	29.5	48.0	3.1	0	0	19.4
Slovakia	1.4	73.9	18.9	0	0	7.2	0
Slovenia	0.5	64.7	35.3	0	0	0	0
Spain	12.4	67	33	0	0	0	0
Sweden	1.2	100	0	0	0	0	0
United Kingdom	4.9	100	0	0	0	0	0

Multiplying the fraction of EU clinker produced in each country by the fraction of clinker produced by a given kiln type in that country and summing this value for all countries should be equal to the total fraction of clinker produced by that technology in the EU given by (Pardo, Moya et al. 2011).

$$\sum_{i}^{27} \frac{clinker\ produced\ in\ country, i}{total\ clinker\ produced\ in\ EU} \times \frac{clinker\ produced\ in\ i\ with\ kiln\ type, j}{clinker\ produced\ in\ country, i}$$
$$= \frac{total\ clinker\ produced\ using\ kiln\ type, j}{total\ clinker\ produced\ in\ EU}$$

Using the above formula, it was possible to determine how much the known production technologies in each country contributed to the total fraction of clinker produced by that technology in the EU. Since some of the production technologies in Romania and Greece were unknown, some fraction of the DL, SD/SW, and W kiln technologies used in the EU were not accounted for. The unknown capacities were assumed to have the same ratio of technology distribution as the yet unaccounted-for DL, SD/SW, and W technologies. The ratio of unaccounted for production technology was DL: SD/SW: W = 0.32:0.4:0.28. The unknown capacities were assumed to have this technology distribution, and thermal efficiency was assumed to be the average of the DL, SD/SW, and W technologies, weighted according to the ratio.

Multiplying the fraction of EU clinker produced in each country by the fraction of clinker produced multiplied by the thermal efficiency of each kiln should give the average thermal efficiency given for all of the EU by the GNR database, 3730 MJ/t clinker.

$$\sum_{j}^{5} \sum_{i}^{27} \frac{clinker\ produced\ in\ country, i}{total\ clinker\ produced\ in\ EU} \times \frac{clinker\ produced\ in\ i\ with\ kiln\ type, j}{clinker\ produced\ in\ country, i}$$
$$\times\ thermal\ efficiency\ of\ kiln\ typ, j \left(\frac{MJ}{t} clinker\right) = 3730\ t/clinker$$

Performing the calculation with the technology production distributions compiled in Table 5 for each country results in an average thermal efficiency of 3724 MJ/t clinker.

Given the fact that the energy efficiency of the unknown capacities in Greece and Romania was determined by using the aggregated data, it is not surprising that the calculated average is close to average given in the GNR database. However, the unknown Greek and Romanian production capacities correspond to less than 1% of the total clinker production in Europe and that the information collected on the kiln technologies used in the non-GNR countries, and the assumptions for thermal energy efficiency are reasonable representation of the European cement industry in these countries.

2.4.6 Fuel input profiles

Determining the fuel input profiles is important because it determines the upstream inputs of obtaining fuel for the clinkering process, and because it provides an indication of expected emissions.

As was the case for kiln types, the GNR database provides aggregated information for fuel input profiles for the EU-27 and for the GNR countries. Fuel inputs are divided into three main groups: fossil fuels, biomass, and fossil fuel wastes. These groups are further categorized into different types of fuels, shown in Table 6.

Table 6: Categories of fuel inputs specified in the GNR database

Fossil fuels	Fossil fuel wastes	Biomass
Coal + anthracite + waste coal	Waste oil	Dried sewage sludge
Petcoke	Tires	Wood, non-impregnated saw dust
Heavy fuel	Plastics	Paper. carton
Diesel oil	Solvents	Animal meal
Natural gas	Impregnated saw dust	Animal bone meal
Shale	Mixed industrial waste	Animal fat
Lignite	Other fossil based wastes	Agricultural, organic, diaper waste, charcoal
		Other biomass

As was the case for kiln technologies, the GNR database provided the distributions of use for each of these fuel types for the EU-27 as a whole and for the GNR countries. The total fuel usage in the EU and in the GNR countries was also given. The average fuel input profile for the non-GNR countries could then be determined by removing the contributions of fuel use by GNR countries from the average. (This is the same procedure used to determine the thermal energy efficiencies of the different kilns used in non-GNR countries.) The average fuel input profile for non- GNR countries is given in Table 7.

Table 7: Fuel input profiles for non-GNR countries

Fossil fuels		**Fossil fuel wastes**		**Biomass**	
Fraction of thermal energy	73 %	Fraction of thermal energy (%)	23 %	Fraction of thermal energy (%)	4 %
Distribution of individual fuels					
Coal , anthracite & waste coal	42.88 %	Waste oil	41.01 %	Dried sewage sludge	24.68 %
Petcoke	53.10 %	Tires	11.93 %	Wood, non-impregnated saw dust	3.47 %
Heavy fuel	0.54 %	Plastics	13.90 %	Paper, carton	2.00 %
Diesel oil	0.13 %	Solvents	4.68 %	Animal meal	43.22 %
Natural gas	0.95 %	Impregnated saw dust	3.20 %	Agricultural, organic, diaper waste, charcoal	0.05 %
Shale	1.75 %	Mixed industrial waste	16.98 %	Other biomass	26.57 %
Lignite	0.63 %	Other fossil based wastes	8.30 %		

For the GNR countries, all of the fuel inputs given in the database are included in the inputs to making clinker. Fuel input information was available for certain plants in non-GNR countries, if so this information was used. In some cases, the types of fuel were given, but not their fraction of thermal input. In such cases, the ratio of fuel types was assumed to be the same as the ratios of fuels calculated for the non-GNR averages.

A review of the GNR data reveals that the sum total thermal energy used in the EU27 cement industry 12% greater than the sum total of energy used in kilns combined.

Table 8: Total thermal energy inputs vs. total kiln inputs in the EU-27

Total clinker (Mt)	Sum total of thermal energy inputs (alternative fossil, biomass, & fossil) (GJ)	Sum total of thermal energy consumed in kilns (GJ)	Relative difference
142	5.45×10^{8}	4.88×10^{8}	12%

Except for a small fraction, less than 0.1%, of fuels which are used in the drying process, the total fuel inputs to cement production are burned in the clinker kiln (Oss and Padovani 2002; Feiz, Ammenberg et al. 2012; Thompson 2012). It was assumed that the discrepancy of fuel use arises from differing ways in which kiln efficiency is measures. The efficiency of a kiln can be measured in the short-term, or in the long-term, which includes efficiency losses due to starting and stopping the kiln as a normal part of plant operation. It was therefore assumed that the total all fuel inputs would be equal to the kiln's nominal efficiency plus 12%.

2.4.7 Emission factors

CO_2 can be predicted based on thermal efficiency and fuel inputs with some certainty provided the carbon content of the fuel is known. Table 9 shows the carbon intensity of fuels used in the EU cement sector. CO_2 emissions were calculated assuming complete combustion of fuel.

Table 9: Carbon intensity of fuels types employed in European cement industry

Fuel type	**kg CO_2/MJ**
Coal, anthracite & waste coal	0.092
Lignite	0.130
Petcoke	0.085
Shale	0.145
(ultra) Heavy fuel	0.064
Diesel oil	0.073
Natural gas	0.051
Waste oil	0.046
Tires	0.079
Plastics	0.074
Solvents	0.067
Impregnated sawdust	0.087
Mixed industry wastes	0.052
Other fossil based wastes	0.052
MSW	0.068
Dried sewage sludge	0.061
wood, non-impregnated saw dust	0.147
Paper, carton	0.089
Animal meal	0.066
Agricultural, organic, diaper waste, charcoal	0.089
Other biomass	0.089

Adapted from: (Kaantee, Zevenhoven et al. 2004; Kellenberger, Althaus et al. 2007; Murray and Price 2008)

2.4.8 Parameters of new cement plants replacing obsolete stock

The above explanations of kiln cohorts, energy use, and technology distributions refer to the mapping of the current cement industry in each European country. To determine how energy use will evolve due to kiln capacity turnover, the parameters of a new plant were chosen.

The new plant used to replace old stock is assumed to be the same for the no CCS and the CCS case. The only difference being that the new plant in the CCS case employs CCS.

It was assumed that new plants will be highly efficient and use large amounts of alternative fuels to simulate a policy amongst cement producers to reduce fuel costs as much as possible. The new plants are assumed to use the PHPC technology with a thermal efficiency of 3300 MJ/t clinker. This thermal efficiency is based on a study identifying the most reasonable lowest thermal efficiency in (Bauer and Hoenig 2010). It is higher than that given by the IEA's estimates shown in Table 1, because the study takes into account efficiency penalties due to starting and stopping the kiln during operation.

The fuel inputs of the new plants are listed in Table 10.

Table 10: Fuel inputs to new model cement plants

Fossil fuels		**Fossil fuel wastes**		**Biomass**	
Share of thermal inputs	40%	Share of thermal inputs	40%	Share of thermal inputs	20%
Distribution of individual fuels					
Coal, anthracite & waste coal	42.88%	Waste oil	41.01%	Dried sewage sludge	24.68%
Lignite	0.63%	Tires	11.93%	Wood, non-impregnated sawdust	3.47%
Petcoke	53.10%	Plastics	13.90%	Paper, carton	2.00%
Shale	1.75%	Solvents	4.68%	Animal meal	43.22%
Heavy fuel oil	0.54%	Impregnated saw dust	3.20%	Agricultural, organic, diaper waste, charcoal	0.05%
Diesel oil	0.13%	Mixed industrial waste	16.98%	Other biomass	26.57%
Natural gas	0.95%	Other fossil based wastes	8.30%		

The distribution of individual fuels within each type of fuel is the same as the average fuel input profile for EU-27 countries, given in the GNR. The fuel input profile of a new plant is simply assumed to have a high thermal substitution rate (TSR) and a high use of biomass. This high TSR and biomass use is representative of existing plants with high thermal substitution rates, and therefore deemed to be feasible for plants built in the near future, but environmentally efficient.

2.5 No CCS case

For the purposes of this model, the CCS case refers to case in which the evolution of emissions and fuel inputs determined by the capacity turnover model explained in section 2.4.

The capacity turnover model represents an evolution of fuel inputs and emissions which is specific to the European cement sector's current and projected technological evolution. Implementing the no CCS case is a matter of setting the fuel inputs and emissions of each country to the corresponding cement sector inputs *A* and *S* matrices of the EXIOBASE model.

2.6 CCS case

To model CCS implementation in the cement sector, it is assumed that the evolution of kiln technology and fuel inputs is the same as is modeled above. The CCS case assumes that all new plants built after 2020 will employ CCS. The amount of CCS inputs needed at a plant per unit output is a function of its CO_2 emissions per unit. It is assumed that plant employing CCS will capture 90% of its emissions.

The CCS process requires material and energy inputs. If cement plants begin to implement CCS, these energy and material inputs must be added to the intermediate demand requirements of the cement sector. Unsurprisingly, the EXIOPOL database does not have a disaggregated CCS sector. To model the inclusion of CCS technology in a given country, the cement sector column of the A matrix was modified to include the sector inputs necessary to operate cement manufacture with CCS. These modifications include extra sector inputs to the cement sector which correspond to the infrastructure, material, and energy needs of CCS capture at a cement plant; they can be divided into the following categories:

Table 11: Overview of CCS life cycle inventory

Input function	Input type
Capture plant	Infrastructure (capital costs)
Pipeline to storage site	Infrastructure (capital costs)
Storage site	Infrastructure (capital costs)
Capture process chemicals	Material inputs (operational costs)
CCS process heat	Energy inputs (operational costs)
CCS process electricity	Energy inputs (operational costs)

2.6.1 Capture costs

2.6.1.1 Capital costs of CO_2 capture

The data collected to quantify the necessary inputs to the cement was mostly in monetary terms, the inputs are hence referred to as costs. Most of the cost data available was in terms of cost per tonne of CO_2 sequestered. In order to convert this to cost per unit monetary output of the cement sector, the costs of CO_2 sequestration were converted to the costs of CCS per € output of the cement sector by normalizing for the CO_2 emissions per € output of the cement sector.

The basic function of the capture plant is to capture the CO_2, run it through the amine scrubber, and conduct it through the transport pipeline. Due to the high energy needs of CCS from the reboiler duty explained in section 2.3.2, several studies recommend the installation of an auxiliary combine heat and power plant to generate to satisfy the extra energy needs (Hegerland, Pande et al. 2006; Barker, Turner et al. 2009).

In this analysis, it assumed that reboiler duty is satisfied by as simply as possible, with a natural gas furnace at the plant because this study assumes that CCS can be implemented for all plants of any size, in any location.

The capital costs are based on IPCC special report with modification of smaller CHP plant according to Hegerland study.

Table 12: Total capital costs of a CCS plant, derived from (Hegerland, Pande et al. 2006)

Cost category	M€
Equipment costs	85.92
Design, erection, construction	123
Contingency fees	38

It is assumed that the lifetime of the plant is 25 years, during which it captures 0.675 Mt CO_2 per year, given that a typical plant produces 0.75 Mt of clinker per year with 0.9 kg CO_2 per kg clinker.

2.6.1.2 O & M costs of CO_2 capture

O & M costs are based on Peeters 2007, which including electricity and fuel costs. Fuel for the reboiler duty is assumed to be natural gas. Extra electricity is needed for CCS to run the cooling water pumps, the CO2 compressor before it is transported, the solvent pumps, etc. Electricity needed to not come from a CHP plant, but from a natural gas energy mix.

Table 13: O&M costs for a CCS plant, excluding electricity, reboiler duty, taxes and labor, purchaser prices (Peeters, Faaij et al. 2007)

Commodity or service	**Cost per tonne of CO_2 avoided (€/tCO2)**
Insurance	0.76
MEA makeup	2.59
Cooling water	0.09
Activated carbon	0.30
Operating supplies	0.46
Plant overhead costs	2.53
R&D costs	0.46
Other costs	0.15
Electricity	0.046
Regenerative fuel (natural gas)	0.035

The costs of natural gas and electricity are based on an assumed reboiler duty of 4.4 MJ per kg CO2 avoided, and 0.5 kWh per kg CO2 avoided, as given in (Peeters, Faaij et al. 2007)

2.6.2 Storage and transport costs

Several studies have analyzed the storage and transport costs of CO2 transport and storage. These costs can vary significantly, but factors such as whether or not the pipeline and storage are onshore or offshore and the mass flow rate of CO_2, are particularly important. Costs for transport and storage chosen for this analysis correspond to onshore piping and storage with a transport distance of 500 km. Most cost estimations are presented as a range, in which case the median was chosen.

The transport of CO_2 chosen for this model is transport via pipeline. Technology for piping CO2 is mature and in use for both above land and underwater (Rubin and de Coninck 2005). The IPCC Special Report on CCS lists the following basic costs of CCS:

- Construction costs
    - Pipeline
    - Telecommunications
    - Possible booster stations
- Operation and maintenance costs
    - Monitoring
    - Maintenance

  - Energy necessary for recompression of CO2
- Other costs
  - Insurance
  - Regulatory fees, etc.

The storage for CCS is assumed to be geological storage transported to the site by pipelines. Geological storage of CO_2 is the process of injecting CO_2 into deep rock formations such as depleted oil and gas reservoirs, coal formations, and saline formations. This type of storage is a commercially mature technology, with current and planned projects around the world (Rubin and de Coninck 2005). It is assumed that this storage corresponds to outputs from the fossil fuel extraction sector, since this sector includes exploration and extraction related services in the EXIOBASE framework.

Table 14: Monetary inputs to CCS (in purchase prices) per kg CO2 avoided, purchaser prices

Sector	**€/kg CO_2**	**Type of expense**
Geological storage	0.00126	Storage
Pipeline transport	0.0047	Transport
Equipment	1.98E-15	Capital
Equipment installation	8.63E-16	Capital
Process piping	1.55E-15	Capital
Electrical	2.59E-16	Capital
Instrumentation	4.31E-16	Capital
Process building	6.98E-16	Capital
Auxiliary building	3.26E-15	Capital
Plant services	1.63E-15	Capital
Site improvement	8.14E-16	Capital
Field expenses	5.82E-16	Capital
Project management	2.56E-15	Capital
Electricity	0.0455	O&M
Regenerative fuel (natural gas)	0.035	O&M
Insurance	7.62E-04	O&M
MEA makeup	2.59E-03	O&M
Cooling water	9.14E-05	O&M
Activated carbon	3.05E-04	O&M
Operating supplies	4.57E-04	O&M
R&D costs	4.57E-04	O&M
Overhead operating costs	2.53E-03	Capital
Other costs	1.52E-04	Capital

The distribution of capital costs into the sectors such as process piping, electrical instrumentation, etc. is based on the commodity distribution of process costs given in (Nguyen 1980).

The total of costs listed in Table 14 put the cost of CCS at 93 €/t CO_2 avoided. This value is high, but still in general given in literature studies.

Table 15 shows the material and input of EXIOPOL sectors to the cement industry per kg capture CO_2 in basic prices.

Table 15: The life cycle material and energy inputs of CCS to and their EXIOPOL sectors, in basic prices

Value (€ per kg CO2 mitigated)	EXIOPOL sector
1.08E-03	Natural gas
8.19E-03	Transport via pipelins
3.19E-04	Manufacture of machinery and equipment n.e.c.
1.16E-15	Manufacture of fabricated metal products, except machinery and equipment (28)
5.80E-16	Manufacture of electrical machinery and apparatus n.e.c.
5.05E-15	Construction
4.94E-16	Real estate activities
2.06E-03	Other business activities
3.28E-02	Production of electricity by gas
2.80E-02	Extraction of natural gas and services related to natural gas extraction, excluding surveying
5.68E-04	Insurance and pension funding, except compulsory social security
1.73E-03	Manufacture of chemicals and chemical products
7.41E-05	Collection, purification and distribution of water
2.16E-04	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
3.91E-04	Research and development
1.19E-04	Other service activities

2.6.3 GHG emissions for the CCS case

A plant employing CCS is assumed to capture 90% of its emissions from cement production, but since this model assumes a simple natural gas boiler to satisfy the reboiler duty, it is also assumed that the emissions from the combustion of natural gas in the boiler are not mitigated. There are also some additional CH_4 and N_2O emissions that occur as a result of the extra natural gas combustion. The added emissions per MJ of natural gas are shown in Table 16.

Table 16: GHG emissions of natural gas combustion

	kg/MJ Natural gas
CO_2	0.059
CH_4	4.26E-06
N_2O	2.13E-06

2.7 Preparing the EXIOBASE database for use in analysis

The EXIOPOL MRIO tables for the time series reflecting the IEA baseline scenario are in the 9x9 region form (hence the 9x9 MRIOT), but the information for material and fuel inputs to the cement sector generated by the capacity turnover model is at a country-by-country resolution, so the 44x44 country EXIOBASE framework (hence the 44x44 MRIOT) was better to use. A time series for the 44x44 MRIOT was derived based on the 9x9 MRIOT.

The regions represented in 9x9 MRIOT are: China, India, OECD Europe, OECD North America, OECD Pacific, Economies in transition, Latin America, Other Developing Asia, and Africa and the Middle East. Each of the 44 countries in the 44x44 MRIOT is part of one of these regions, with the exception of the rest of rest of the world (RoW) countries which belong to several regions. A matrix of the individual countries and their corresponding regions can be found in Appendix G.

The 9x9 MRIOT was based on 138 sectors in each region, because some of the electricity production sectors were disaggregated. Before creating a time series for the 44x44 MRIOT model, these sectors were re-aggregated.

To create a time series for the 44x44 MRIOT, it was assumed that the background changes over time in the 9x9 MRIOT were the same as for the 44 region model. For example, it was assumed that the Belgium-to-China section of the 44x44 MRIOT model would have the same background changes between 2013 and 2030 as the OECD Europe to China section of the 9x9 MRIOT requirements matrix because Belgium is part of OECD Europe. Each country-to-country sector of the 44x44 MRIOT was multiplied by the ratio of changes between one model year to the next given in the part of the9x9 MRIOT model corresponding to the regions containing these countries.

If the ratio of the requirements of one sector to another was infinity from 2013 to 2030, or from 2013 to 2050, because the 2013 value was 0, the value for that sector-to-sector exchange was assumed to be the same as for the correspond exchanging in the 9x9 MRIOT. For example of the ratio sector inputs from Chinese rubber to Belgian tire production was infinity from 2013 to 2030 because the 9x9 MRIOT indicates that the OECD Europe tire sector does not import any rubber from the Chinese sector in 2013, but begins to do so in 2030. In this case, the value of import of Chinese rubber to the Belgian tire sector in the 2030 version of 44x44 MRIOT time series is assumed to be the same as the value given for Chinese rubber to OECD Europe tires in the 2030 9x9 MRIOT.

2.7.1 Considerations for adjusting the values of the A and S matrices

Now that a time series for the 44x44 MRIOT had been established, the inputs to Europe's cement sectors and the direct emissions from these sectors was adjusted by placing the calculated fuel and input values of the no CCS and CCS cases directly into the corresponding values of the A matrices and S matrices of the 44x44 MRIOT times series.

For example, for the no CCS case, the inputs of coal to the Belgian cement sector had been calculated and the CO_2 emissions of Belgian's cement sector had been calculated for the years 2013, 2030, and 2050. Inputs of coal to the Belgian cement sector for each model year of the 44x44 MRIOT time series were set to equal the calculated values of coal inputs, and the CO_2 emissions per unit output of this sector were set to equal the model-derived CO_2 emissions.

The 44x44 MRIOT is units of year 2000 MEuros in basic prices. The prices of fuels, cement, and CCS inputs were determined, adjusted for inflation to 2000 Euro values, and converted purchasing prices to basic prices by using the ratio of purchaser prices to basic prices given in the most recent Supply and Use Table (SUT) for the French economy. The details of this process are explained in Appendix E.

2.7.1.1 Distributions of importing countries

For inputs of a given sector it was assumed that distribution of intermediate demand amongst import countries remained the same for the cement region. For example, if the cement industry of Belgium is calculated to need 1 kWh of extra electricity per unit output of cement due to CCS, and the requirements matrix in EXIOBASE lists the Belgian cement industry as obtaining 50% of its electricity requirement per unit output domestically, 30% from France, and 20% from Germany, it is assumed that this ratio holds. Per unit output of cement, Belgium would then obtain 0.5 kWh domestically, 0.3 kWh from France, and 0.2 kWh from Germany in order to satisfy the new demand of electricity needed for CCS.

For the CCS case in particular, it happened that the cement industry of a given country did not require inputs from certain sectors at all according to the 44x44 MRIOT. In that case it was assumed that these new requirements were satisfied by domestic industries. For example, before the implementation of CCS, the 44x44 MRIOT may have listed the imports of chemicals from any country to the Danish cement industry as 0, because without CCS, the Danish cement industry does not MEA or other chemical inputs. It was therefore assumed that chemical inputs necessary for CCS implementation in Denmark would come from the Danish chemical industry.

2.7.1.2 GHG values of the no CCS and the CCS case

In the no CCS case only the values in the S matrix which correspond to CO2 emissions are changed according to fuel inputs and thermal efficiencies calculated using the capacity turnover model. The values of CH_4 and N_2O per unit sector output are left unchanged, because the emissions factors of these gases are more difficult to predict when alternative fuels are used.

For the CCS case, the combustion of natural gas to satisfy the reboiler duty will definitely result in an increase in CH_4 and N_2O emissions. The new emissions factors of these gases per unit output of cement are calculated and added to S matrix.

3 Results

3.1 The European Cement Industry

Figure 3 and Figure 4 show how the cement industry in Europe will evolve from 2013 to 2050 terms of CO_2 emissions and kiln types.

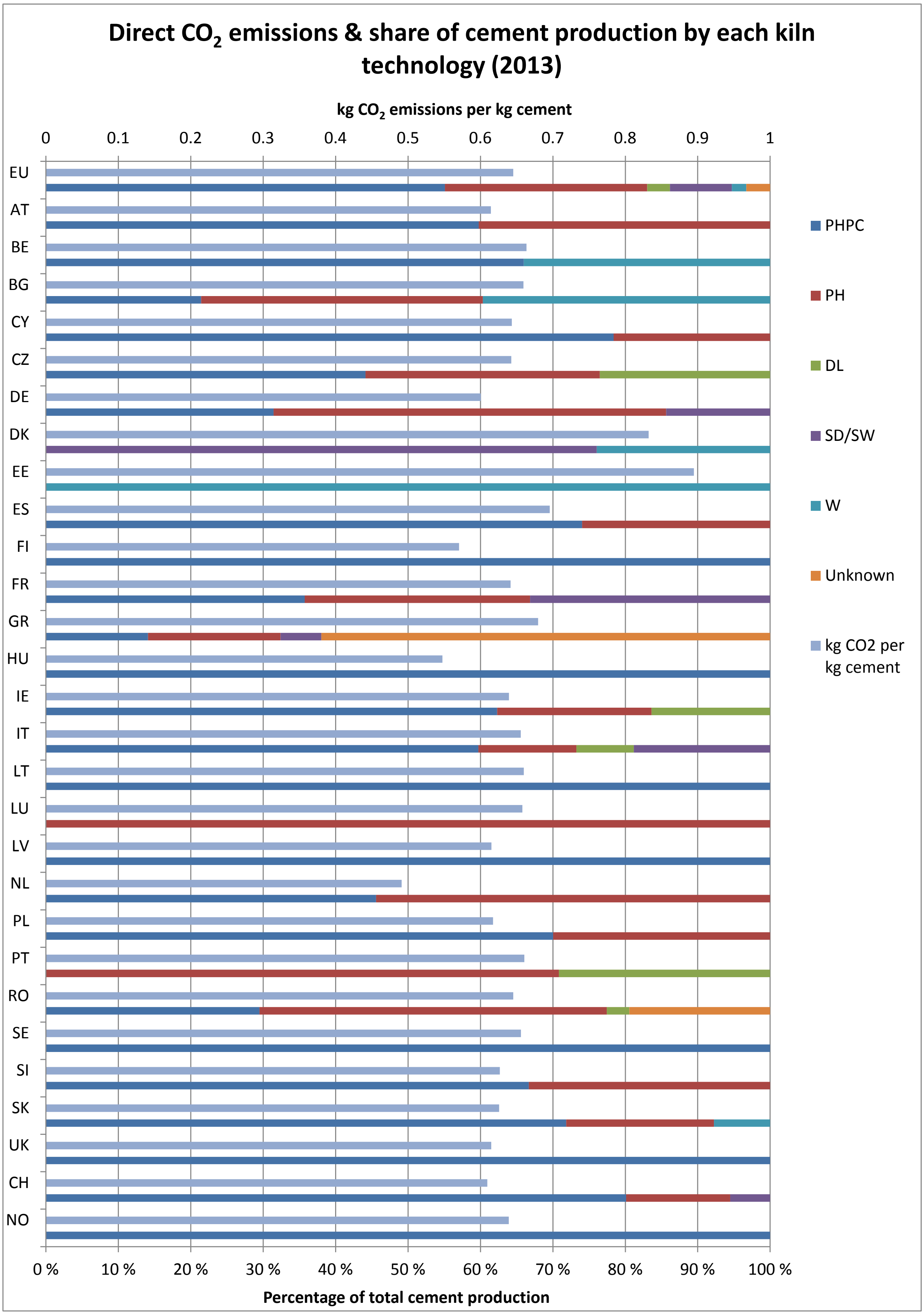

Figure 3: Direct CO_2 emissions per kg cement produced, compared to kiln distribution technology for all countries and the EU average in 2013

Figure 3 shows that average direct CO2 emissions per country vary significantly. The graph shows that countries with a higher percentage of capacity covered by wet or semi-dry/semi wet kilns tend to have higher CO_2 emissions, such as Estonia and Belgium. However, due to the variation in thermal efficiency of PHPC, PH, and DL kilns, the differences between countries employing a mix of these kilns is not as significant..

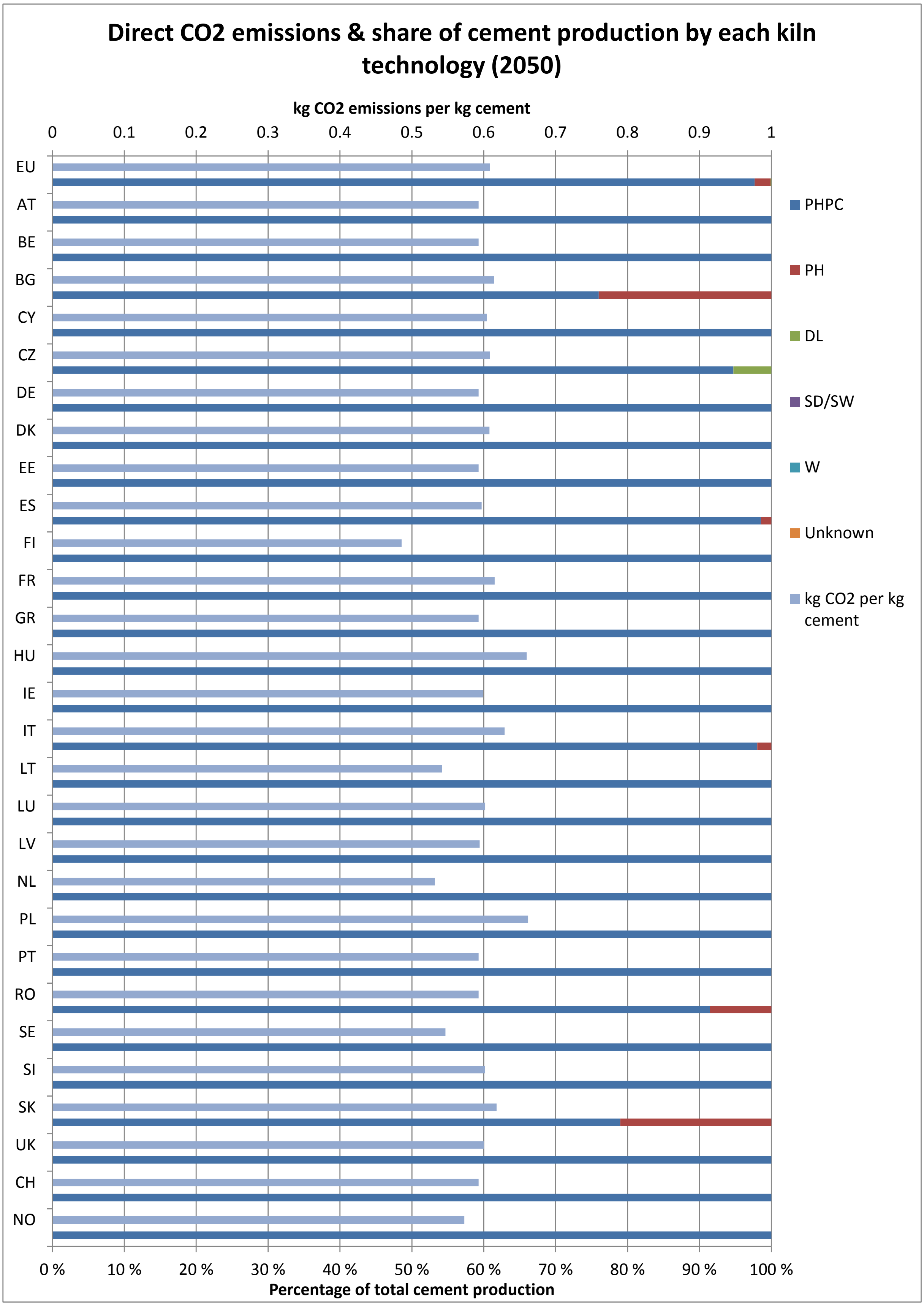

Figure 4: Direct CO_2 emissions per kg cement produced, compared to kiln distribution technology for all countries and the EU average in 2050

Figure 4 shows that by 2050, more than 95% of cement production will occur using the most efficient PHPC technology. Consequently, the direct CO_2 emissions per kg of cement are reduced from 0.65 kg direct CO2 per kg cement to 0.61 kg CO2, a reduction of 5.7%. This is similar to the findings in the similar study by (Pardo, Moya et al. 2011) which performed a capacity turnover model the EU as a whole.

One reason that the reduction is so small is that some of the current PHPC kilns which are not old enough to go out of stock by 2050 are not thermally efficient. For example, the current average PHPC kilns in Austria and Poland are 3820 MJ/t clinker and 3850 MJ/t, respectively. The cohorts of PHPC kilns for GNR countries are assumed to be spread from 1984 to 2002. As such, some of these old, inefficient PHPC kilns will still be in stock by 2050.

In certain countries where the most inefficient kiln types currently account for a large share of cement production, such as Estonia or Italy, the reductions in direct CO_2 emissions are more significant. This can be explained by the fact that these industries were much more inefficient than the European average to begin with, meaning the opportunities for improvement were larger.

The results in Figure 4 also indicate that the changing fuel distribution does not play a large role in direct CO_2 emissions. While alternative fuels offer the benefit of reduced indirect emissions because they are not extracted from the environment as petcoke and coal are, combustion of any fuel still emits carbon, and alternative fuels do not necessarily emit less carbon per unit energy than fossil fuels.

Another significant reason for which CO_2 emissions for Europe as a whole do not change much is because more than half of the direct emissions are a result of the calcination of limestone in the cement kiln. For the new model PHPC kiln which replaces all old stock, the emissions from fuel are 0.2675 kg CO_2 per kg clinker, while the CO_2 emissions from fuel are 0.53 kg per kg clinker. The model does not assume a clinker factor that changes over time and the emissions contribution from calcination remains the same.

3.2 Carbon Capture and Storage in European cement industry

Figure 5 shows the rate at which integrated capacity of cement production using CCS will grow, given that all new plants built during and after 2020 will employ CCS.

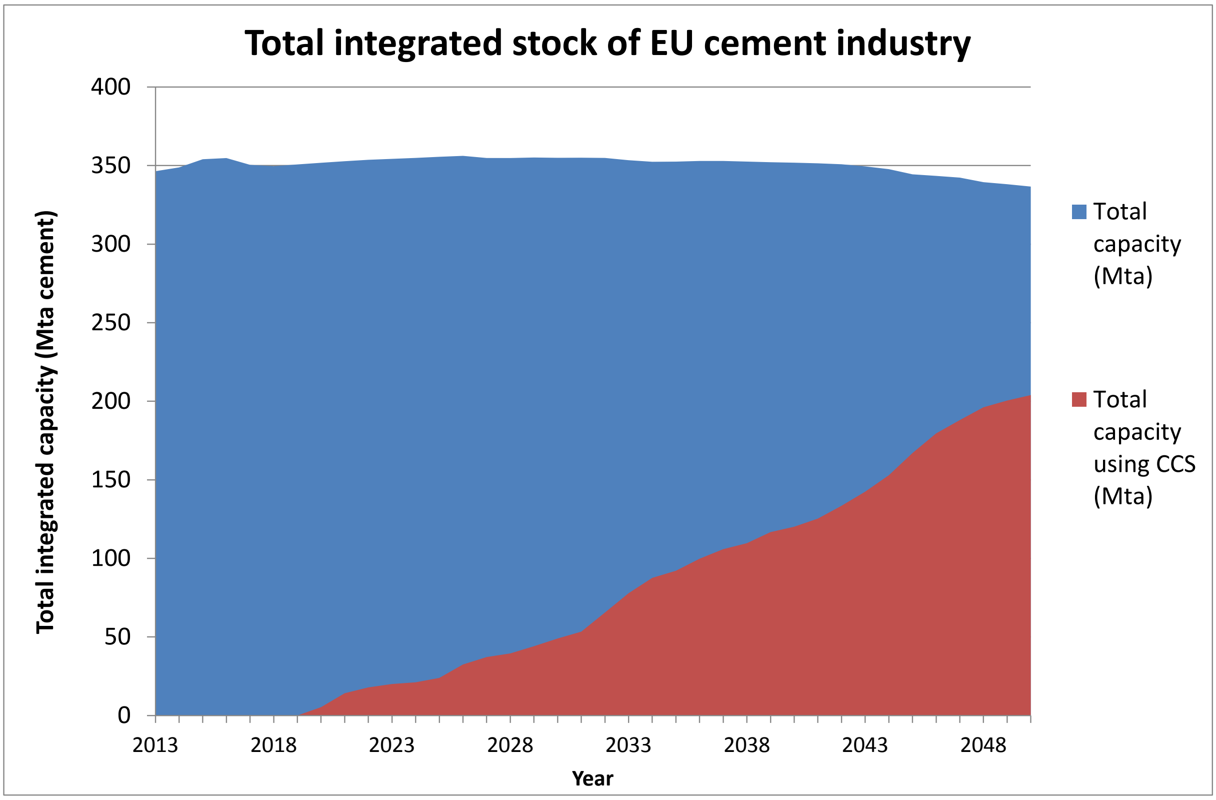

Figure 5: Total integrated capacity of the EU cement industry and total capacity using CCS

This shows the evolution of the total integrated capacity of the European cement industry according to the commodity intensity curve employed in the capacity turnover model. This is because, over time, the capacity will begin decrease, as the countries of Europe pass into an economic phase where they require less cement per capita. The constant capacity from the present year until 2040 is due to the Economies in Transition, such as Romania and Bulgaria, which will increase their demand for cement, as the GDP per capita of these countries grows and cement will be necessary to build infrastructure and vault the populations in to a western European standard of living.

Figure 5 shows that the share of integrated capacity implementing CCS will reach 61% by 2050, if all new integrated cement plants after 2020 are built with CCS. This also illustrates the rate of capacity turnover in the EU after 2020, by 2050 61% of Europe’s cement kilns will be newer than the 2020 cohort.

3.3 Total global warming Potential of the EU cement industry

Now that the changes in emissions per unit cement output and the rate at which CCS will be implemented has been observed, the implications of these changes are placed in the economy wide context and the total global warming impact in kg CO2-eq of the EU cement sector can be observed.

Figure 6 shows the total production-based impact of global warming of each country's cement sector for the case where CCS is not implemented and the case where CCS is implemented in all new cohorts after 2020. These are the results the expression $D_{sector} = CS\hat{x}$ for when the adjusted A and S matrices of the 44x44 MRIOT time series.

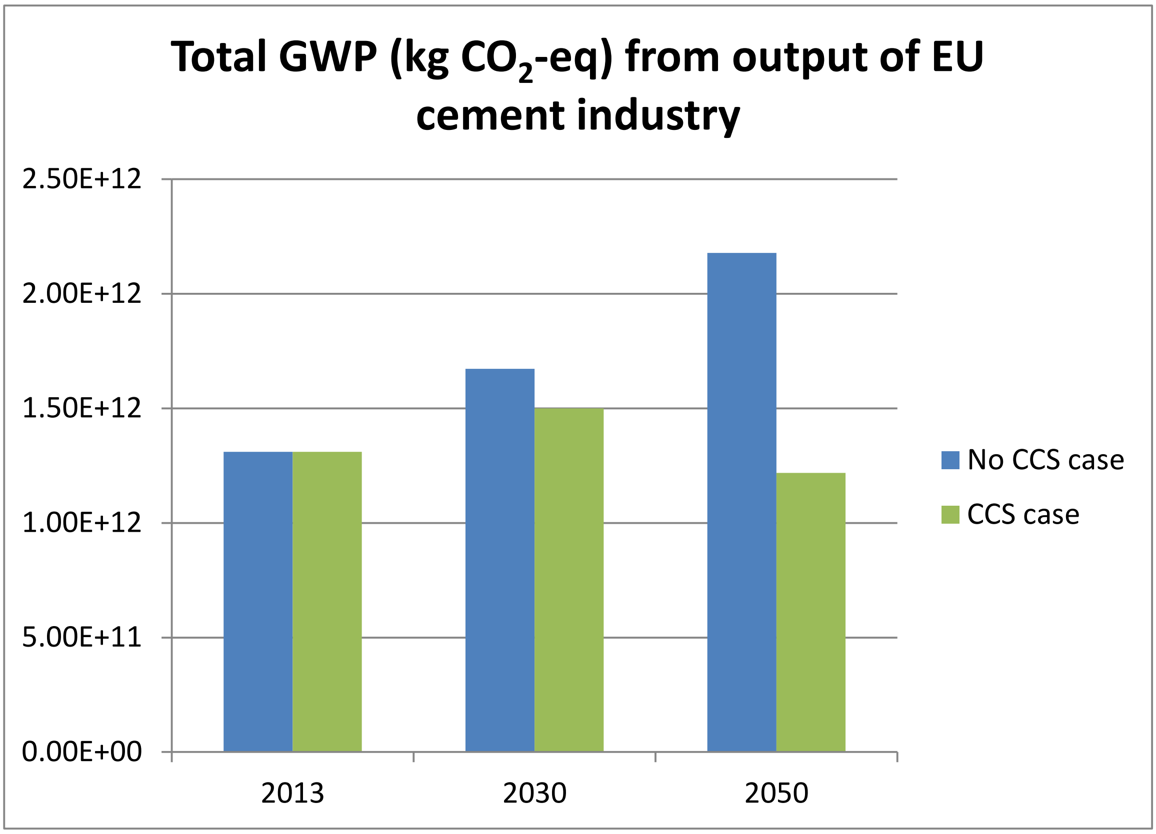

Figure 6: Total GWP of EU cement industry, as a result of output from the cement sector

Figure 6 shows that without CCS, the impacts to global warming as a result of direct emissions from the cement sector will increase, despite the fact that Figure 3 and Figure 4 the CO_2 emissions per unit of cement are shown to decrease. The increase in impact to global warming is due to the fact that demand for cement is assumed to increase over time in the EXIOBASE model. This means that the emissions from total cement production increase, even though the emissions per *unit* cement output decreases.

The difference in GWP between the no CCS case and the CCS case is small in 2030 because only a small fraction of Europe's cement plants have begun to implement CCS by this time. The difference between the CCS case and the non-CCS case in 2050 indicates that the cement sector could nearly halve its emissions for a given output, if only 61% of the total sector employ CCS.

Figure 7 shows the total global warming impact due to the demand of cement from each European cement sector for the case where CCS is not implemented and the case where CCS is implemented after 2020.

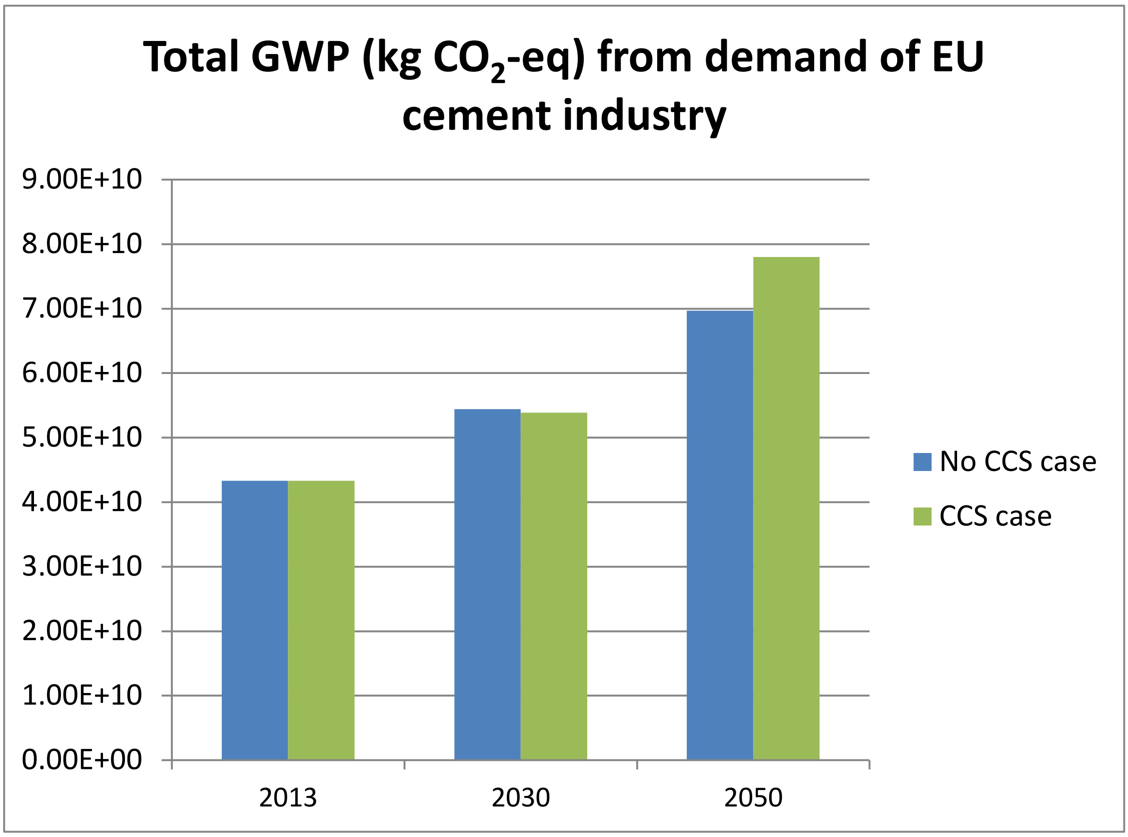

Figure 7: Total GWP of the EU cement sector as a result of demand of the cement sector

Figure 7 differs from Figure 6 in that Figure 6 reflects the direct emissions from the cement industry, as a result of exogenous demand placed on all sectors of the economy, while Figure 7 illustrates how the emissions from the upstream processes of cement production and the direct emissions of cement production contribute to global warming.

The total values are larger in Figure 6, which output based impacts, than in Figure 7, which shows demand based impacts, because the total output of a sector will always be larger than the final exogenous demand from a sector. This is because the total output of sector includes the intermediate demand placed on the sector by inter-industry requirements, plus the total exogenous demand placed on the sector.

The fact that CCS implementation in the EU in 2050 leads to a higher GWP as a result of cement demand means the global warming impact per unit final demand of cement has increased, and that implementing CCS in 2050 for the cement industry will *increase* the GWP of the entire world economy, despite the fact that direct emissions from the cement industry have decreased. This is confirmed by Figure 8, which shows the total GWP for the world economy for the MRIOT framework without adjustments, the no CCS case, and the CCS case.

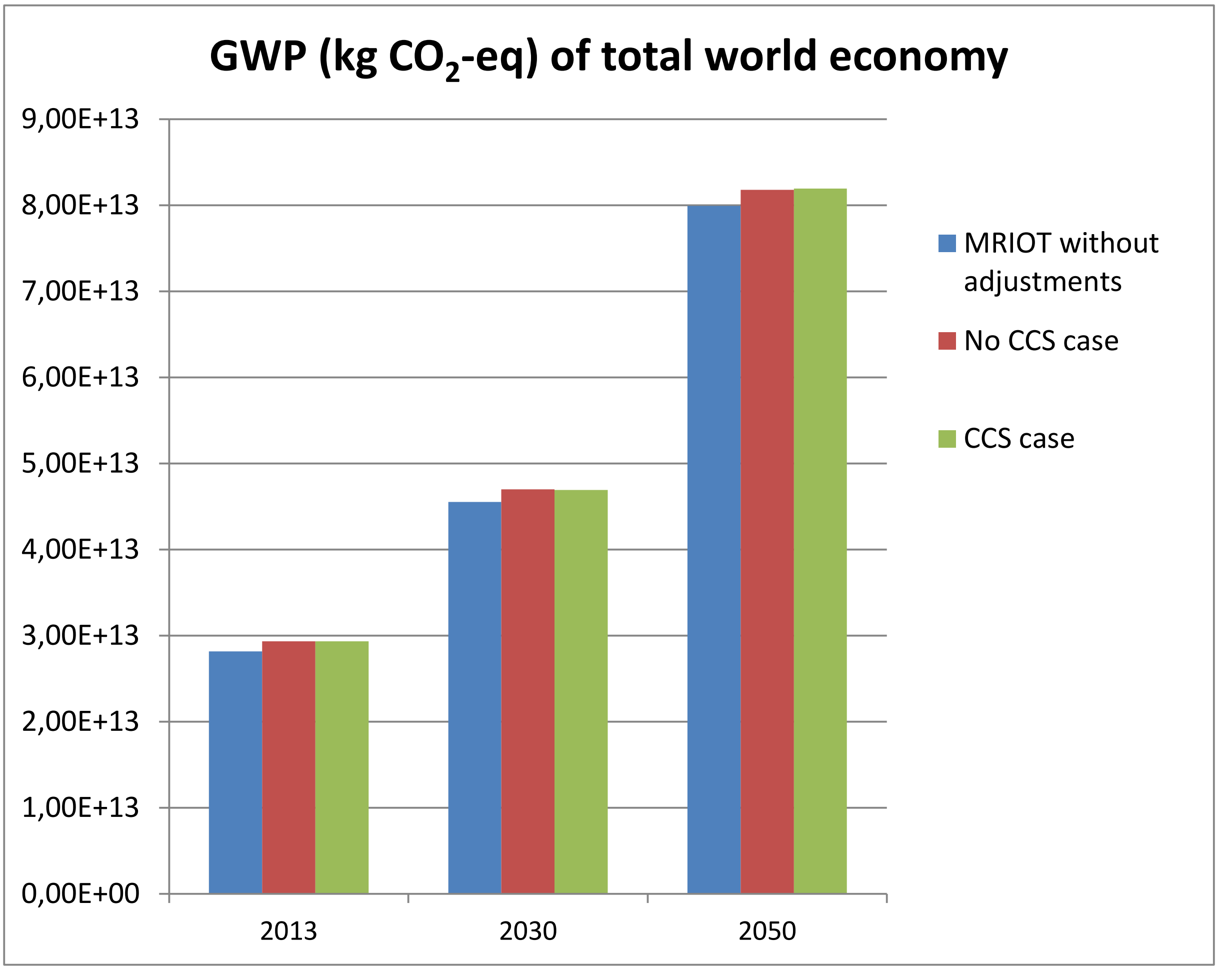

Figure 8: GWP of world economy for using the MRIOT framework without adjustments, the no CCS case, and the CCS case

The small difference in results of the MRIOT framework without adjustments and the no CCS case show that fuel input and CO_2 adjustments made to the MRIOT model are most likely reasonable. Additionally, Figure 8 does show a slight increase total GWP for the CCS case. It is not as visible as in Figure 7, because the total GWP is much higher.

When CCS is implemented, the cement sectors require more upstream processes because CCS requires extra inputs. Figure 7 and Figure 8 show that by 2050, when CCS is implemented for 61% of European cement production, the increased upstream emissions from the extra sector inputs required for CCS are greater than the direct decrease in emissions of the cement sector due to CCS. For 2013, the impacts are the same because CCS is not yet implemented. However, Figure 7 shows that in 2030 the upstream emissions of the cement sector due to CCS are slightly smaller than the emissions savings due to CCS.

The reason for this can be seen in Figure 9 and Figure 10, which show the GWP impact of the cement industries of individual countries for the no CCS and CCS cases, using output and demand allocation respectively.

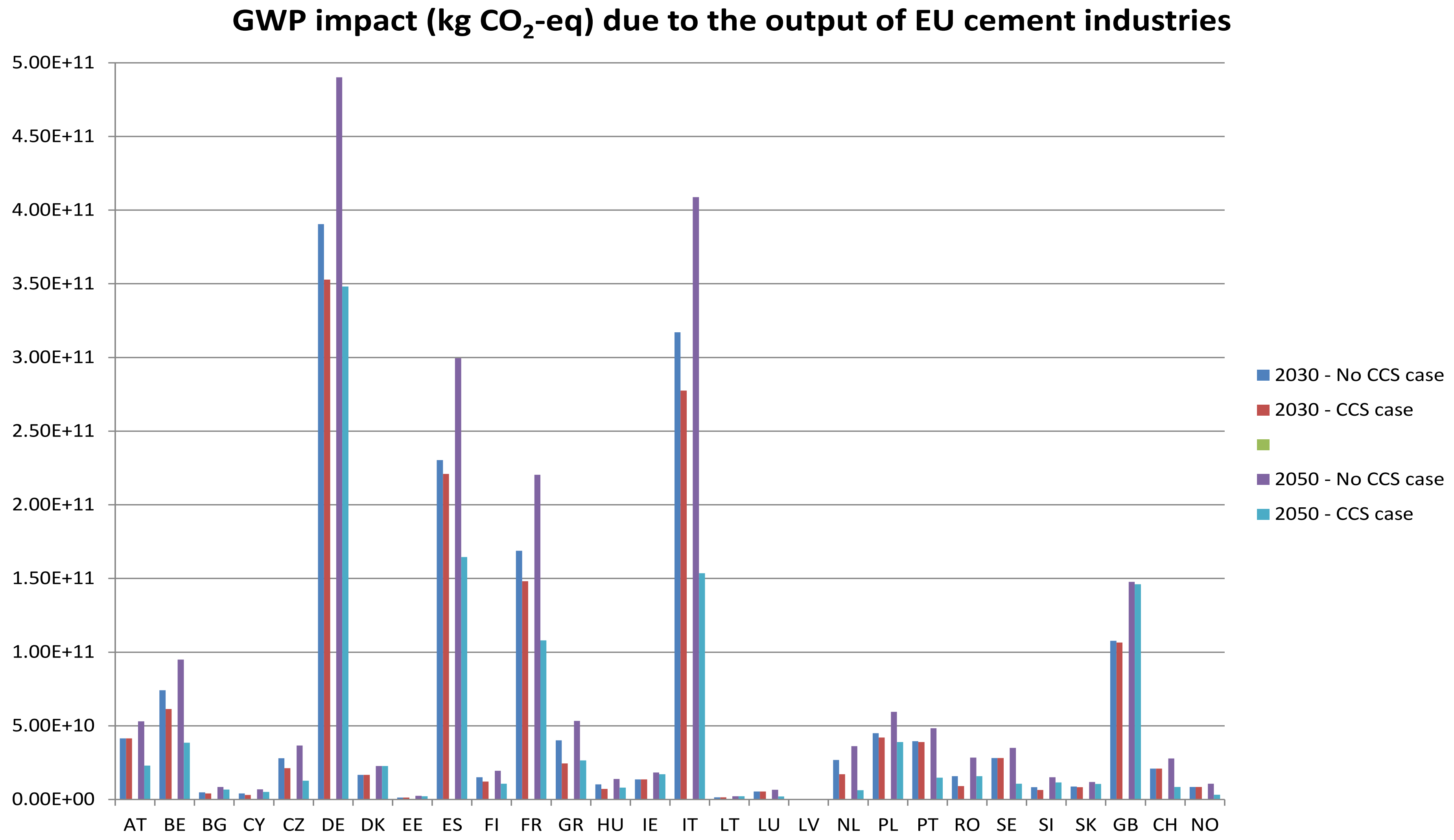

Figure 9: GWP impact (kg CO_2-eq) due to the output of individual EU cement industries

Figure 9 shows that for all countries, the production based GWP impact of cement is smaller with CCS than without. In the cases where the impacts are the same for a given year, such Austria in 2030, it is because CCS has not been implemented in Austria by 2030, because no new plants are being built between 2020 and 2030.

Some variation in the difference between the two cases can be seen for the individual countries. This reflects the variations in the rate at which CCS is implemented in individual countries. Countries that currently have newer plants, such as Great Britain, will have little new stock in 2050, meaning that CCS will be implemented for a smaller fraction of the country’s total cement sector. Countries such as Italy, which currently have more old plants, will have switched out much of their stock by 2050, meaning that CCS will be implemented for a large fraction of total cement production.

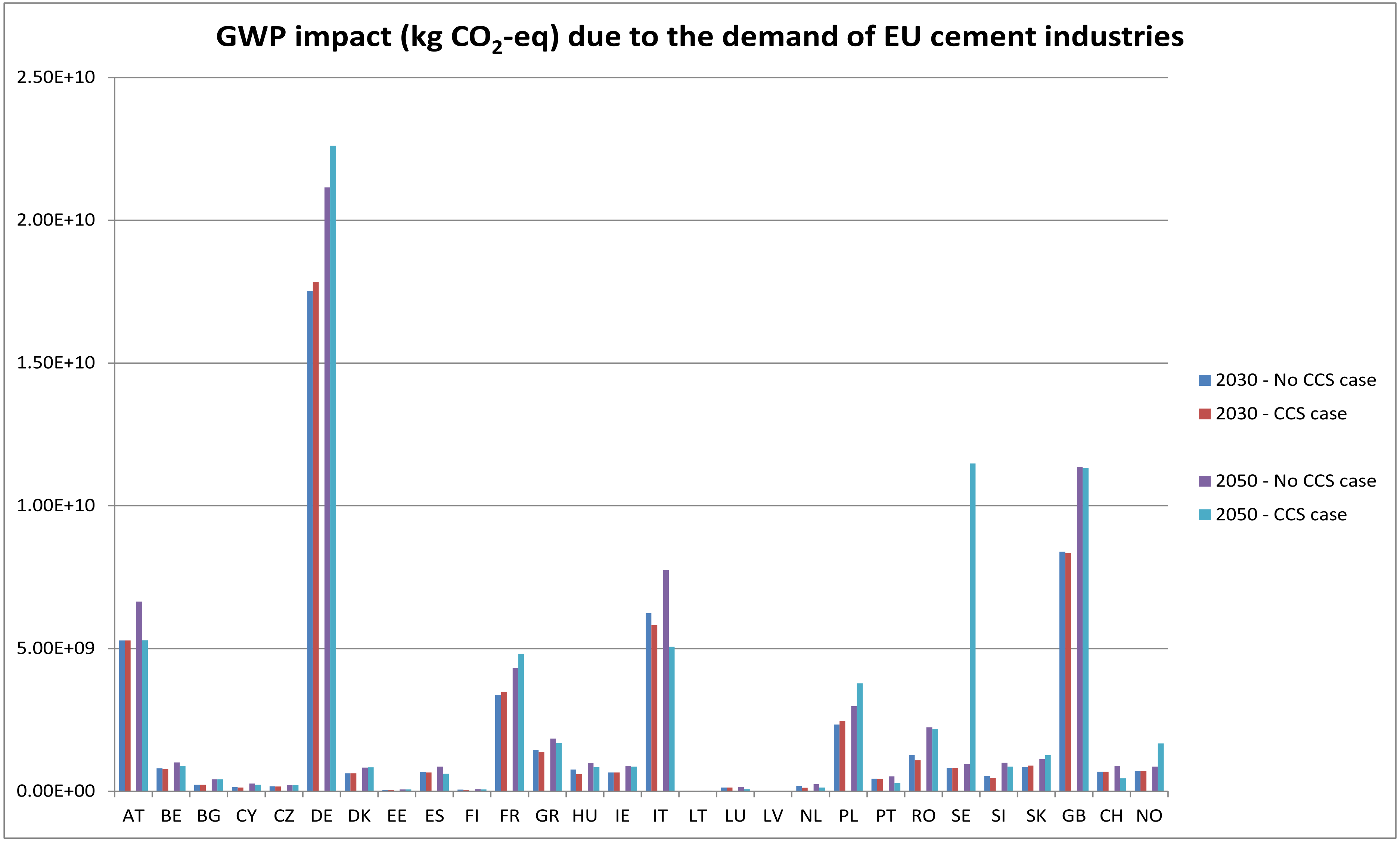

Figure 10: GWP impact of (kg CO2-eq) due to the demand of cement industries in individual EU countries

Figure 10 shows that the upstream impacts of CCS vary greatly from country to country. In certain cases, the CCS case still results in a lower global warming impact. Since the MRIOT model reflects the fact that different countries satisfy their intermediate demand requirements from different trade partners, the upstream impacts can vary greatly. For example the upstream impacts of the extra CCS inputs differ greatly in the case of Italy and Sweden, which are in different areas of the continent.

It is possible that Sweden imports more commodities from Eastern Europe to satisfy the additional intermediate demand imposed by CCS implementation than Italy, which may import from countries with cleaner industries. These differences may also arise from differences in the environmental performance of Italian and Swedish industries.

The variation in CCS performance across countries also explains why the CCS case generates slightly better results in 2030. In 2030, CCS is employed across Europe to a lesser extent than in 2050, and it is employed by countries whose environmental performance improves slightly with CCS. These countries include Italy, Greece, Hungary, Romania, and others who have old kiln capacity which will soon go out of stock.

3.3.1 Important contributing sectors for the CCS case.

To determine which industries contribute most to the increased GWP of the CCS case, the impacts of producing 1 M€ of cement with and without CCS were determined for three countries: Sweden, Italy, and France. These countries were chosen because they have three different results of consumption based impact allocation for the CCS case, compared to the no CCS case. The GWP impact was calculated using the following expression:

$$D_{sector} = CSL\widehat{y}$$

The exogenous demand, y, was 1 M€ of cement from the countries in question. D_{sector} was calculated for each case for the three model years, and the top twenty contributing sectors were identified for each model year. For the non CCS case, the same sectors made the largest contribution to global warming during each model year. For the CCS case, certain sectors made a significant impact to global warming in years 2050, but not 2030 or 2013. This shows that these sectors were most important when CCS is implemented at the highest rate, and their impacts were therefore a result of CCS implementation. Table 17 shows which sectors were most important in the CCS case for each country and their percentage of the total GWP impact of producing 1 M€ of cement in that country.

Table 17: Most important sectors contributing to global warming impact of cement, specific to the CCS case

Sweden			**Italy**			**France**		
Sector type	Country of sector	% contribution to GWP	Sector type	Country of sector	% contribution to GWP	Sector type	Country of sector	% contribution to GWP
Electricity from natural gas	DE	0.016%	Coal, lignite, and peat	GR	0.11%	Electricity from natural gas	BE	0.45%
Electricity from natural gas	DK	0.041%	Sea and coastal water transport	IT	0.10%	Electricity from natural gas	DE	0.15%
Casting of metals	SE	0.015%	Manufacture of chemicals	RU	0.13%	Electricity from natural gas	IT	0.15%
Mining of iron ores	SE	0.005%	Sea and coastal water transport	RU	0.21%	Natural gas	RU	0.33%
Natural gas	SK	0.032%	Casting of metals	RU	0.22%	Natural gas	NO	0.12%
Natural gas	GB	0.024%	Electricity from coal	RU	0.18%	Manufacture of rubber and plastic production	WW	0.06%
Transport via pipelines	CA	0.020%	Electricity from natural gas	RU	0.18%	Electricity form coal	WW	0.09%
Transport via pipelines	RU	0.009%	Steam energy	RU	0.16%			
Natural gas	NO	0.126%	Transport via pipelines	RU	0.13%			

Table 17 shows that for the countries where the GWP impact of cement production is larger with CCS, Sweden and France, the reboiler duty and extra electricity needs are deciding factors in the system's environmental performance. It is possible that the extra impacts from natural gas and electricity from natural gas are due to the upstream requirements of other inputs to CCS. However the fact that this fuel and electricity mix consistently feature as the new processes which contribute the largest portion of GWP to the CCS cases indicate that the direct inputs to CCS of natural gas and electricity from natural gas significantly decrease the environmental performance of the CCS case.

Another reason that CCS performs worse in 2050 than in 2030 is that as fossil fuel supplies dwindle, extracting them becomes more energy intensive. By 2050, the GWP of extracting natural gas will thus increase, meaning that the environmental cost of the reboiler duty increases as well.

3.3.2 Alternative scenarios

This analysis employs many parameters which are subject to uncertainty. Two parameters which are of particular importance are the clinker factor, and the reboiler duty for CCS. The clinker factor used in cement is important because clinkering is the most energy- and emissions-intensive part of cement production. The results shown in Table 17 indicate that the natural gas needed to satisfy the reboiler duty is a determining factor in the environmental performance of a CCS system. Two alternative scenarios were tested to determine to what degree the improvement of these two parameters will improve the environmental performance of cement production.

Other parameters are important, such as the electrical energy needed in the CCS process, but clinker factor and reboiler duty are tested here because the reduction of these two parameters is technologically feasible in the near future.

The lowest average clinker factor for any GNR country is 0.681 in Germany. The no CCS case was run assuming that every EU country had such a low clinker factor by 2030, instead of the average of 0.737.

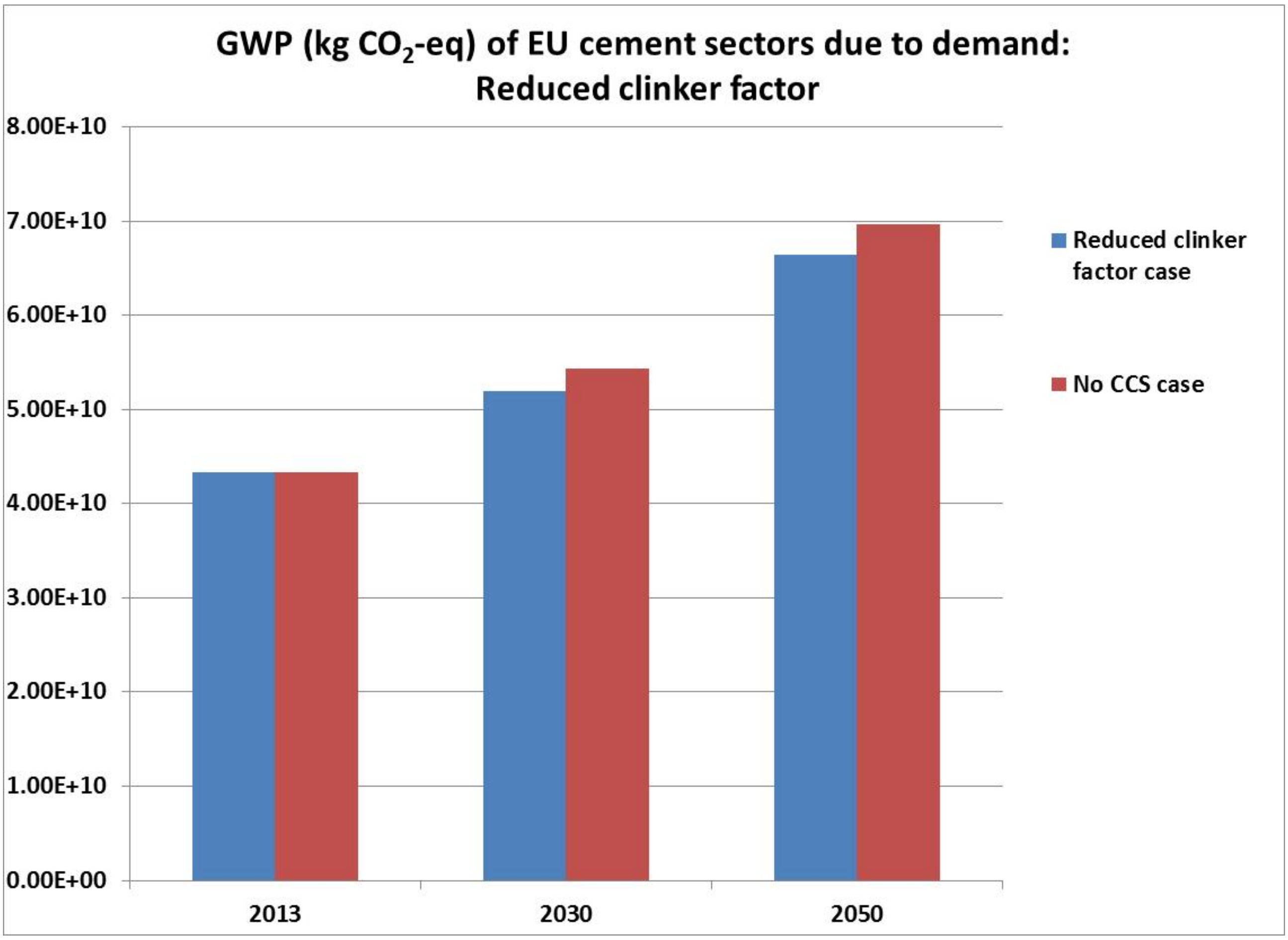

Figure 11: Comparison consumption based GWP of the no CCS case using the average clinker factor and the reduced clinker factor of 0.681

Figure 11 shows a reduction in GWP due to total demand of cement of 4% for 2030 and 5% in 2050 if the average clinker factor is reduced from 0.74 to 0.681. This means that reducing the clinker factor by 8% reduces the total consumption based GWP by 4% in 2030, showing that the system's environmental performance is very sensitive to the clinker factor.

The GWP due to demand was calculated for the CCS case using a reboiler duty of 1.6 MJ per kg CO2 captured, as opposed to 4.4 MJ which is used in the CCS case. This value reflects a feasible, medium term improvement in CCS technology which can be obtained by 2030 (Peeters, Faaij et al. 2007). Figure 12 shows the results of this.

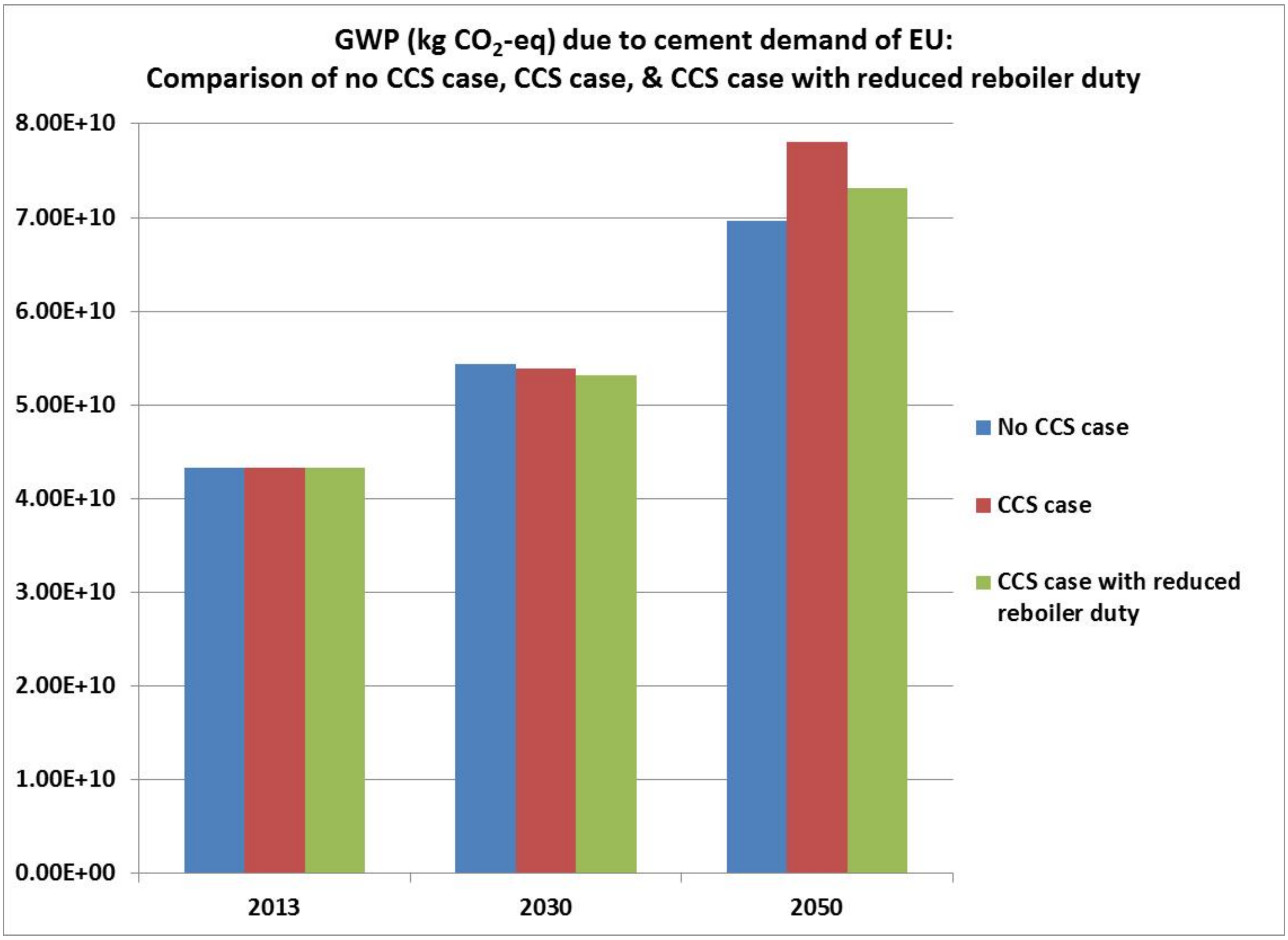

Figure 12: GWP due to EU cement demand for the no CCS case, the CCS case, and the CCS case with reduced reboiler duty

Reducing the reboiler duty by 64%, 4.4 MJ per kg CO_2 to 1.6 MJ/kg CO_2, results in a 6.2% GWP reduction. Improving the reboiler duty improves the overall economic performance of the CCS case, but not enough for it to be the better option by 2050. The improvement in the performance of the CCS case with a reduced reboiler duty confirms the results of Table 17. The natural gas procurement necessary to supply the energy for the reboiler duty is one of the most important factors affecting the environmental performance of the system. However, the system is less sensitive to changes in the reboiler duty than to changes in the clinker factor.

4 Discussion

4.1 Implications of results

The results of the analysis can be summarized with a few key points. The first is that the there is significant opportunity to reduce the thermal efficiency of cement in certain countries were old kilns are still in use, but for Europe as a whole the majority of cement production is relatively efficient. While encouraging greater thermal efficiency is still important for the industry, great changes in the impact to global of cement production in Europe due to kiln turnover are not expected. The European cement sector is thus technologically mature.

This means that the European cement producers, such as LaFarge and Holcim, which are expanding into cement markets in the developing world, where less efficient kilns are still common, can reduce GWP of cement worldwide by applying their skills and expertise in operating the most efficient technology in order to speed up the technological maturity of cement sectors in the developing world.

As expected, the implementation of CCS reduces the global warming impact of cement output. However, the total GWP due to the *demand* of cement increases in Europe when CCS is employed. This means that the total emissions embodied in cement increases when cement is used. An important implication of these results is that CCS will not provide a solution for reducing the emissions of the cement industry by 50%. While the production based allocation of GWP results show that the direct emissions of the cement industry can be reduced by nearly 50% compared to the non-CCS case, the CCS case corresponds to an increase in GWP. This finding is important on a practical and research level in that it shows how inter-sector interactions and trade can affect the performance of the system as a whole. In the case of CCS with cement, the inter-industry activity instigated by changes in the cement industry to implement CCS have a negative effect on the world-wide economy’s environmental performance. For researchers, this illustrates the importance of fields such as input-output analysis which quantify interactions between industries.

On a practical level, the results of the analysis mean that an actual reduction of GWP from the cement industry will require a more radical change in cement production than simply increased alternative fuel use and CSC.

Increased GWP due to the demand of cement is not the result of CCS implementation in all countries. This is due to the fact that individual countries employ and import goods from different production technologies, whose environmental performance varies. The variation in the performance of CCS illustrates the importance of where the extra inputs to CCS are produced. In general, the processes that contribute most to the increased GWP of cement with CCS are natural gas for the reboiler duty and the electricity needs of CCS.

Given the uncertainty regarding prices, the source of energy for the reboiler duty, and the energy mix for the electricity used in CCS inputs, the results of this analysis prove at the very least, that further study is needed before the EU policy makers can determine with certainty that CCS in use with cement will have any positive effect on the GWP of Europe’s economy. However, due to the fact that some countries can use CCS with cement production to reduce GWP per unit demand of cement, this technology could still be useful for the cement industry.

The increased GWP due to the reboiler duty and the extra electricity confirm the findings of other studies, which imply that CCS for industrial processes will perform best when linked with a power plant as suggested in (Naranjo, Brownlow et al. 2011). For example, a large cement plant can operate near a CHP plant, which efficiently produces a surplus of low exergy heat that cannot be used for electricity but can be used to satisfy the reboiler duty. In such a case, the heat from the CHP plant is a by-product of electricity production meaning that the CCS process at the cement plant is not creating new demand for fossil fuels.

This kind of set-up also offers the advantage that two point sources of carbon emissions would be located near each other. If CCS is employed for both the CHP and cement plant then they could share the economic and environmental burden of the capture, storage, and transport infrastructure and operation. Since pipeline transportation, and sea and coastal transport were also important sectors contributing to the GWP of CCS, as shown in Table 17 using the inputs of these sectors more efficiently will also reduce the upstream impacts of CCS use.

If the case is that combining CCS, cement, and power production reduces the GWP per unit demand of cement and power, then CCS is an option which will most likely not be suitable for small plants in areas far away from other industries. A fruitful policy could be to provide incentives for large cement manufacturers to work in conjunction with CHP plants and to employ CCS at these sites. Smaller cement manufactures can reduce their footprint through simpler means, such as thermal efficiency improvements, clinker factor reductions, and alternative fuel use.

The importance of the energy mix for CCS implies that renewable alternative fossil fuels, electricity derived from low-carbon sources, and reducing clinker factor are more environmentally and economically sound means of reducing the global warming impact of the cement sector, especially in the short term.

4.2 Weaknesses of the model

4.2.1 Simplicity of fuel input assumptions

The fuel inputs of the existing plants are assumed to remain static, although certain plants are actively increasing their alternative fuel inputs. This means that inputs of fossil fuel will decrease over time more quickly than the results show. However, there was seldom information on the plans for increasing alternative fuels. This means that modeling an increase in alternative fuel usage over time at existing plants would also have required another group of assumptions regarding the type of fuels used, the rate at which alternative fuel use increase, the final replacement rate, etc. The uncertainty that these assumption would have generated would have lessened the value of the results.

4.2.2 IO modeling

The cement, plaster, and lime sector were not disaggregated. It was assumed that the cement was the dominant product in terms of total output. The inputs and emissions calculated for the individual countries directly for the cement production were therefore placed directly into the A and S matrices of the model without scaling or taking plaster and lime production into account. For more accurate results, the cement, lime, and plaster sector could be disaggregated and the calculated inputs could be inserted into the cement sector.

This simplification could explain the increase in GWP results for the world-wide economy for the no CCS case, compared to the results of the 44x44 model without adjustments. It is possible that the emissions per unit output of cement are higher than the emissions per unit of an average bundle of cement, lime, and plaster from the sector.

A source of uncertainty in the model is likely the means with which prices valuations were determined. The differences in purchase prices and basic prices for the French sectors were used to estimate prices, but this can lead to uncertainty if there are certain French industries which are more heavily taxed or subsidized than the European average.

4.2.3 Reconciling the two data sets for demand

The entire modeling process for the analysis utilizes a demand factor for cement twice: the first time to determine the rate of plant turnover in the EU cement industry using the commodity intensity curve shown in Figure 2, and the second time when calculating the total GWP of the cement industry using the EEXIOBASE data, which contains demand projections for all sectors of each country. For the purposes of this model, these two data sets of future cement demand were not reconciled. The demand calculated by commodity intensity was used to determine the kiln turnover rate, and thus the thermal energy requirements of cement manufacture in each country. Using the commodity intensity curve method to determine the capacity turnover rate was preferred because it allows for a continuous calculation of capacity turnover.

Additionally, some apparent balancing errors were found in the *y* vectors given in the EXIOBASE data, these values for demand may have had significant errors in the case of individual countries. Ideally, the cause of the balancing errors in EXIOBASE would have been found and fixed, and the two sets of data for exogenous demand of cement would have been reconciled. The difficulty with this is that the EXIOBASE data for demand indicates that the demand for cement will continue to increase over time. This is most likely based on a basic assumption used in the model that increased GDP translates to increased consumption of all commodities. This assumption is true for many commodities, but in reality the demand for cement will most likely remain stable for some years and economies in transition build their infrastructure, and then decrease as GDP increases.

The implication of these two conflicting trends for demand of cement is that the total output from the cement sector will most likely not increase at a rate as high as indicated by the EXIOBASE data. On one hand, this is good news for the fight against global warming because it means that consumption of a carbon intensive commodity will decrease or stabilize over time. On the other hand, the commodity will still be in demand for the near future, and the eventual decrease in demand will not translate into the emissions reduction goals set forth by the IPCC.

4.3 Suggestions for further work

In light of the fact that CCS is not a viable option for reducing global warming for every cement plant, an interesting study would be to create a bottom up model of cement plants in Europe that could work in conjunction with nearby CHP plants. A similar analysis to this one could be carried out, by adjusting the inputs to the cement and power sector of the EXIOBASE model to determine how these new plants will affect the GWP of the entire economy.

Given the fact that CCS does have significant impacts to other categories such as toxicity (Singh, Strømman et al. 2011), a study which covers more than one impact category would be worthwhile in determining to what extent widespread CCS use would affect toxicity levels in Europe.

Using the EXIOBASE MRIO model has proven to yield interesting information regarding the trade interactions of each country, and working with a model of so many countries gives practitioners the flexibility to use higher resolution, country-specific data. However, as discussed in the section 4.2.3 there seem to be some over-simplifications in the demand projections. For commodities such as cement, whose demand per capita decreases with GDP, it would be interesting to refine these demand projections to reflect the decreasing or stabilizing consumption trends. This would help identify which sectors will shape the environmental performance of the economy in the future. Further research in how to best reduce the emissions from these sectors could then be carried out. Since the important sectors of the future may be in the early stages of their infrastructure and technological development, inefficient practices can be avoided before they become entrenched in the business as usual practice of the sector.

5 Conclusion

5.1 Assessment of goals

The goals to be accomplished in this study have been achieved. For the cement sectors of the 28 European countries studied, technology and cohort distributions were established, thermal efficiency fuel input data were collected, and the capacity turnover and evolution of CO_2 emissions from cement production of each country were determined. An economic life cycle inventory of CCS implementation for cement was established, and a cradle-to-gate assessment of the cement production with and without CCS implementation was performed using the EXIOBASE multi-regional input-output model.

The goal of adding higher resolution to the cement sector has been achieved, particularly for the non-GNR countries and the EU countries which fall into the "Economies in Transition" category. In the case of these countries, the practice of fuel and energy reporting is a new or non-existent practice. Given the possible lack of consistent and reliable information for energy and emissions from these countries and the variation in energy use and emissions in the cement sector, building a bottom-up model to determine these parameters is more accurate than extrapolating them based on estimations from other countries. The information on individual cement industries collected in this report can be used for further LCA or IOA studies of cement production.

The bottom-up model of capacity turnover for the cement industry in each country confirms the work of Pardo et al. (2011), showing that the evolution of clinker production technology yields a reduction in CO_2 emissions in cement of about 6%.

The cradle-to-gate analysis of cement production with CCS has filled a knowledge gap in the field of environmental analysis by illustrating that, for Europe as whole, CCS with cement leads to an increase in GWP in the whole economy. However, the GWP due to cement demand varies from country to country. This illustrates the importance of mapping trade flows to determine impact embodied in the consumption of products. The variation in GWP results from country to country also illustrates the importance of using cleaner energy mixes, and illustrates the effects of varying production technologies, particularly for fossil fuels.

The data gathered for this report can be used for further research, and results of this report carry implications for policy makers, but the knowledge gap has not been completely filled.

The most important question: that of how the European cement sector will reduce its emissions by 50% by 2050 remains unanswered. However, this analysis shows that the tools for answering this question do exist. With databases such as EXIOBASE, and methodologies such as IOA to determine quantify the flow of energy, goods, and services in the between regions and over time, environmental researchers have the ability to identify the most important sectors contributing to present and future global warming. This information can be used to shape technological development and policy-making to avoid future emissions and halt the effects of global warming.

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Appendix A Cement plant information

This is the appendix that shows how the country inventories are made...

Most of the sources for this information come directly from company websites...

When energy or electricity inputs are given, the data point for the most recent year is taken. Although energy efficiency can vary, it is assumed that the most recent data point, rather than an average, is the best estimation because a plant is constantly working to optimize processes and improve efficiency.

Belgium

Gaurain-Racecroix	Compagnie des ciments Belges (CCB) Italcementi		
Capacity (Mta cement)	2.4	Technology information	Cement grinder is a roller mill.
Kiln type	PHPC	Renovation information	Kiln 4, the largest kiln in Belgium, put online in 1987.
Energy use	NA	Fuel inputs	20% TSR, MSW. Coal and petcoke fossil fuel inputs.
Electricity use	NA		

Sources: (Perez 2012) (CCB Italcementi Group 2007) (CCB Italcementi Group 2008)

Obourg and Haccourt	Holcim		
Capacity (Mta cement)	2.8	Technology information	NA
Kiln type	Wet process	Renovation information	2 kilns constructed in 1960s
Energy use	NA	Fuel inputs	56.8% TSR, mostly industrial wastes. Coal fossil fuel inputs.
Electricity use	NA	Additional information	Haccourt produces blast furnace slag cement using clinker from Obourg (Edwards 2012). Obliged to use wet process due to moisture content of raw materials.

Sources: (Perez 2012) (European Commission) (Edwards 2012)

Lixhe	CBR (HeidelbergCement Group)		
Capacity (Mta cement)	1.5	Technology information	A ball mill for cement grinding was installed in 1995. SNCR to be installed in 2013.
Kiln type	PHPC	Renovation information	4-stage PHPC kiln put online in 1976. The plant was expanded in 2000, allowing them to mothball the wet kilns dating back to 1968.
Energy use	NA	Fuel inputs	62.2% TSR, 37.5% of which was biomass. Alternative fuels consist of plastics, impregnated sawdust, industrial liquids, and car tires. Except for car tires, the alternative fossils fuels are bought from Resofuel, constituting 24.5% of energy inputs. Biofuels consist of sewage sludge mixed with sawdust.
Electricity use	NA		

Sources: (Lixhe 2012)

Antoing	CBR (HeidelbergCement Group)		
Capacity (Mta *clinker*)	0.95	Technology information	Kiln burner replaced in 2011, allowing for the combustion of alternative fuels.
Kiln type	PHPC	Renovation information	The kiln was started in 1986. Produces clinker used by CBR's grinding factories at Gand, Rotterdam, and Ijmuiden. (The latter two located in the Netherlands.)
Energy use	NA	Fuel inputs	62% TSR, 52% biomass. Alternative fuels consist of dry industrial and sewage sludge, plastics, MBM, paper, textiles. Fossil fuels consist of petcoke and coal.
Electricity use	NA		

Sources: (ENCI 2011) (Antoing 2012)

Gand	CBR (HeidelbergCement Group)		
Capacity (Mta cement)	1.5	Technology information	
Kiln type	None	Renovation information	Total renovation in 2000.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Grinding station produces blast furnace slag with clinker from other sites.

Sources: (ENCI 2011)

Harmignie	CBR (HeidelbergCement Group)		
Capacity (Mta cement)	0.2[a]	Technology information	Clinker ground in a rotary ball mill.
Kiln type	Wet process	Renovation information	NA
Energy use	NA	Fuel inputs	44% TSR, 12.36% of which is biomass. Non-renewable alternative fuels include plastics.
Electricity use	NA	Additional information	Produces white cement. Obliged to use wet process due to moisture content of raw materials

[a] Inferred from total capacity for CBR in Belgium given as 3.2 in (Perez 2012).

Sources: (ENCI 2011) (CBR Harmignies 2012)

Bulgaria

Devnya Tsiment	Italcementi		
Capacity (Mta cement)	2	Technology information	Uses planetary clinker cooler.
Kiln type	Wet	Renovation information	Investment was approved for replacing kilns in 2007. They were not replaced as of 2010.
Energy use	NA	Fuel inputs	Fossil inputs are petcoke and coal mix. 0% alternative fuel use.
Electricity use	NA	Additional information	98 g dust/t clinker, 3882 g NO_x/t clinker, 1660 g SO_2/t clinker for Italcementi Bulgaria. Italcementi group Bulgaria produces white cement.

Sources: (Brininstool 2012) (Devnya Cement 2010) (Devnya Cement 2012) (Italcementi Group Bulgaria 2010) (Devnya Cement 2010) (World Cement 2006)

Dimitrovgrad	Vulkan Cement (Italcementi)		
Capacity (Mta cement)	0.5	Technology information	NA
Kiln type	Wet	Renovation information	4 wet kilns installed in 1947, 1948, 1953, & 1965.
Energy use	NA	Fuel inputs	0% alternative fuel use.
Electricity use	NA	Additional information	Italcementi group Bulgaria produces white cement.

Sources: (Brininstool 2012) (Devnya Cement 2010) (Devnya Cement 2010) (Italcementi Group Bulgaria 2010) (Devnya Cement 2012)

Beli Izvor	Holcim		
Capacity (Mta cement)	1.7	Technology information	NA
Kiln type	PH (assumption based on renovation info)	Renovation information	5 oldest kilns were shut down in 1990. 6th kiln mothballed in 1998. Kiln 7, the last kiln, upgraded in 2004 with new preheater.
Energy use	NA	Fuel inputs	48.8% TSR. 31379 tons recovered solid waste (31%) , 9076 tons MBM (7%), 5640 tons tires (7%), & 4806 sunflower husks (3%).
Electricity use	NA	Additional information	

Sources: (Brininstool 2012) (Holcim Bulgaria 2012) (Holcim Bulgaria 2011)

Holcim's Plevenski cement plant, with a capacity of 0.6 Mta cement, was closed for good in 2011.

Zlatna Panega	Titan Cement		
Capacity (Mta cement)	1.5	Technology information	NA
Kiln type	PHPC and dry process (assumed from renovation information)	Renovation information	In 2004, 1 old kiln replaced, 2nd kiln upgraded, new hybrid filters installed on kilns, new vertical mill commissioned. Two 1500 tpd lines now in use.
Energy use	NA	Fuel inputs	10% TSR, consisting of old tires. Coal is main fossil fuel.
Electricity use	NA	Additional information	

Sources: (Brininstool 2012) (Titan Bulgaria 2013) (Titan Cement 2010) (Titan Bulgaria 2013) (World Cement 2006)

Cyprus

Moni	Cyprus Cement Co. Ltd.		
Capacity (Mta cement)	0.4	Technology information	Satellite coolers. 1 vertical mill, 2 ball mills.
Kiln type	2 stage PH	Renovation information	New production line installed in 1975.
Energy use	NA	Fuel inputs	0% TSR. Coal as fossil fuel.
Electricity use	NA	Additional information	Produces grey Portland cement and pozzolan cement.

Sources: (Newman 2013) (Cemnet 2004) (Cyprus Cement Company Ltd. 2002)

Vassiliko	Vassiliko Cement Works		
Capacity (Mta cement)	1.26	Technology information	Roller type cement mill installed 2002.
Kiln type	New line PHPC	Renovation information	A new production line was put into operation in 2011, with 4,500 tpd clinker capacity. (Whether or not the SW lines were shut down was unclear from sources. Assumed all production with PHPC for this report.)
Energy use	NA	Fuel inputs	New kiln can burn HFO, coal, and alternative fuels. Company provides no information about alternative fuels used, most likely still in development phase.
Electricity use	NA	Additional information	The plant owns four kilns, 3 were in operation as of 2009 with a capacity of 3600 tpd clinker. Produces white cement.

Sources: (Newman 2013) (World Cement 2009) (Vassiliko Cement Works 2013) (CEMBUREAU 2002) (World Cement 2006)

Bogaz	Bogaz Endustri ve Madencilik (Holcim)		
Capacity (Mta cement)	0.15	Technology information	NA
Kiln type	none	Renovation information	NA
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Grinding station. Clinker was sourced from Lebanon as of 2003, but clinker is assumed to be from the largest domestic source for the purposes of this report.

Sources: (Newman 2013) (Holcim 2013)

Czech Republic

Radotin	HeidelbergCement		
Capacity (Mta cement)	0.8	Technology information	Grate cooler for clinker cooling.
Kiln type	4-stage PH (2 kilns)	Renovation information	Plant was modernized in 1996.
Energy use	3.65 MJ/kg clinker	Fuel inputs	62.5% TSR for Heidelberg cement in Czech Republic. Incinerates oil wastes, BMB, plastics, textiles. Fossil fuels include lignite and coal.
Electricity use		Additional information	

Sources: (Soto-Viruet 2012) (Českomoravský cement 2011)

Mokra	HeidelbergCement		
Capacity (Mta cement)	1.4	Technology information	A new air and dust filter was commissioned in 2004.
Kiln type	PH	Renovation information	
Energy use		Fuel inputs	62.5% TSR for Heidelberg cement in Czech Republic. Incinerates oil wastes, BMB, plastics, textiles.
Electricity use	NA	Additional information	

Sources: (Soto-Viruet 2012) (Českomoravský cement 2008)

Hranice	Dyckerhoff AG		
Capacity (Mta cement)	1.1	Technology information	NA
Kiln type	3 stage precalciner	Renovation information	Plant was originally built to use wet process, but was modernized to use dry process in 1987. Modernization to include precalcination occurred in 1992.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	

Sources: (Soto-Viruet 2012) (Cement Hranice 2008) (Cement Hranice 2007)

Cizkovicka	LaFarge		
Capacity (Mta cement)	1.2	Technology information	NA
Kiln type	5 stage PHPC	Renovation information	Cyclone precalciner replaced original heat exchanger in 1995.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	NA

Sources: (Soto-Viruet 2012) (LaFarge Cement 2012) (LaFarge Cement 2012)

Prachovice	Holcim		
Capacity (Mta cement)	1.2	Technology information	Fabric filters installed between 2003-2006.
Kiln type	Dry process (Most likely dry long based on renovation info and energy use)	Renovation information	New plant with dry method built between 1977-1980.
Energy use	3901 MJ/t clinker	Fuel inputs	35911 tons RDF used in 2011. Coal is the main fossil fuel input. Total energy use in 2011 was 2009674 GJ.
Electricity use		Additional information	Produces grey and white cement

Sources: (Soto-Viruet 2012) (Holcim (Česko) a.s. 2010) (Holcim (Česko) a.s. 2012)

Detmarovice	Cemex		
Capacity (Mta cement)	0.4 (Assumed based on total capacity in Czech republic.)	Technology information	
Kiln type	Dry process (based on GNR energy use data for Czech Republic)	Renovation information	Plant expanded in 2005.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	NA

Source: (Cemex S.A.B. 2010)

Denmark

Rordal	Aalborg Portland		
Capacity (Mta cement)	2.7 grey 0.85 white	Technology information	NA
Kiln type	Semiwet for grey cement, Wet for white cement	Renovation information	NA
Energy use	4.61 GJ/TCE grey 6.96 GJ/TCE 6230 GJ/t grey clinker (assuming 74% clinker factor) 7326 GJ/t white clinker (assuming 95% clinker factor)	Fuel inputs	Grey cement: 28% TSR 20% CemMiljø-brennsel, 1% MBM, 1.5% glycerin, 4% tires, 1.5% paper. White cement: 9% TSR, consisting of MBM. For all cement: 31 kg coal/TCE 115.6 kg petcoke/TCE 4.1 kg fuel oil/TCE
Electricity use	115 kWh/ton TCE	Additional information	Produces grey and white cement.

Sources: (Newman 2013) (Aalborg Portland 2010) (Aalborg Portland 2011)

Estonia

Kunda	Kunda Nordic (Heidelberg Cement)		
Capacity (Mta cement)	1.0	Technology information	Ball mills for cement grinding
Kiln type	Wet process	Renovation information	The current factory dates back to the 1960s. The plant was renovated from 1993-2000 with focus on eliminating dust from kilns and cement mills.
Energy use	NA	Fuel inputs	Fuel inputs 2009: 132 kt oil shale 47 kt coal 3.2 kt shale wastes 3.8 kt waste oil 3.2 kt waste solvents 12.3 kt RDF 0.5 kt plastics
Electricity use	120 kWh/ t cement	Additional information	

Sources: (Kunda Nordic 2012) (Kunda Nordic 2012) (Kunda Nordic 2010)

Finland

Pargas	Finnsementti		
Capacity (Mta cement)	0.9	Technology information	
Kiln type	PHPC (assumption based on energy use)	Renovation information	NA
Energy use	2.9 kJ/kg TCE 3.6 MJ/ kg clinker (Finnsementti total)	Fuel inputs	21.6% TSR. Incinerates SRF. Incinerates coal and petcoke. (Finnsementti total.)
Electricity use	112 kWh/kg TCE	Additional information	Finnsementi produces white cement. 0.05 kg dust/t clinker 1.4 kg NOx/t clinker 0.03 kg SO2/t clinker

Sources: (Newman 2012) (Finnsementti Ltd. 2012)

Lappeenranta	Finnsementti		
Capacity (Mta cement)	0.6	Technology information	NA
Kiln type	PHPC assumed based on renovation information	Renovation information	Kiln was built in 2007
Energy use	3.0 kJ/kg TCE 3.6 MJ/ kg clinker (Finnsementti total)	Fuel inputs	21.6% TSR, goal is to have 40% TSR. Incinerates SRF. Incinerates coal and petcoke.
Electricity use	112 kWh/kg TCE	Additional information	0.05 kg dust/t clinker 1.4 kg NOx/t clinker 0.03 kg SO2/t clinker 0.03 kg SO2/t cement

Sources: (Newman 2012) (Finnsementti Ltd. 2012)

Greece

Kamari	Titan Cement Company		
Capacity (Mta cement)	2.6	Technology information	Grate cooler
Kiln type	4-stage PH	Renovation information	Plant established in 1976. 2 kilns.
Energy use	NA	Fuel inputs	10% TSR, dried sewage sludge.
Electricity use	NA	Additional information	Emissions with conventional fuels: 100 mg dust/Nm3 1200 mg NOx/Nm3 400 mg SO2/Nm3 0 mg TOC/Nm3 Emissions with alternative fuels: 30 mg dust/Nm3 800 mg NOx/Nm3 50 mg SO2/Nm3 10 mg TOC/Nm3

Sources: (Newman 2013) (Titan Group 2010) (Katsiamboulas 2007)

Thessaloniki	Titan Cement Company		
Capacity (Mta cement)	2.0	Technology information	Grate cooler, vertical cement mills.
Kiln type	5-stage PHPC	Renovation information	1 kiln, new line built in 2003.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	NA

Sources: (Newman 2013) (Titan Group 2010) (Katsiamboulas 2007)

Elefsina	Titan Cement Company		
Capacity (Mta cement)	0.4	Technology information	NA
Kiln type	NA	Renovation information	Plant established in 1902.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Produces white cement only.

Sources: (Newman 2013) (Titan Group 2010) (Katsiamboulas 2007)

Patras	Titan Cement Company		
Capacity (Mta cement)	1.7	Technology information	NA
Kiln type	NA	Renovation information	Plant established in 1968. 2 kilns.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	NA

Sources: (Newman 2013) (Titan Group 2010) (Katsiamboulas 2007)

Halyps	Italcementi		
Capacity (Mta cement)	0.8	Technology information	NA
Kiln type	SD/SW (assumed renovation information and capacity information)	Renovation information	Upgrades have occurred continuously from 1991 to 2004, taking capacity from 0.5 Mta to 0.8 Mta. Kiln had previously been renovated in 1980 to increase the daily production of clinker to 1,500 tpd; it is now 2,000 tpd.
Energy use	NA	Fuel inputs	0% TSR
Electricity use	NA	Additional information	NA

Sources: (Newman 2013) (LaFarge 2013)

Volos	Heracles		
Capacity (Mta cement)	4.5	Technology information	NA
Kiln type	NA	Renovation information	The two most recent production lines installed in 1971 and 1976.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	NA

Sources: (Newman 2013) (LaFarge 2013) (LaFarge 2013)

Milaki	Heracles		
Capacity (Mta cement)	2.2	Technology information	New system installed to cut down NOx and dust emissions in 2008.
Kiln type	Dry process (based on renovation information)	Renovation information	Operation started in 1982.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	

Sources: (LaFarge 2013)

Haklis	Heracles		
Capacity (Mta cement)	2.6	Technology information	NA
Kiln type	NA	Renovation information	NA
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Idle since 2011. The decision to close it down completely was made in 2013.

Sources: (Newman 2013) (ICR Newsroom 2013)

Hungary

Beremend	Duna Drava Cement (Heidelberg Cement)		
Capacity (Mta cement)	1.4	Technology information	NA
Kiln type	4-stage PHPC	Renovation information	Clinker production process modernized in 2009, including kiln modernization increasing capacity from 1500 tpd to 3450 tpd new clinker cooler.
Energy use	NA	Fuel inputs	Incinerates secondary fuels: 41% rubber, 21% paper/textile/biomass/wood, 22% BMB, 16% biomass. Alternative fuels approximately 18% of thermal heat.
Electricity use		Additional information	Emissions info: 35 g dust/t clinker 1273 g NOx/t clinker

Sources: (Anderson 2013) (Duna-Dráva Cement Kft. 2009) (World Cement 2009)

Vac	Duna Drava Cement (Heidelberg Cement)		
Capacity (Mta cement)	1.1	Technology information	A new ball mill cement grinding plant was commissioned in 2003.
Kiln type	PHPC	Renovation information	NA
Energy use	NA	Fuel inputs	Incinerates secondary fuels: 41% rubber, 21% paper/textile/biomass/wood, 22% BMB, 16% biomass. Alternative fuels approximately 18% of thermal heat.
Electricity use	NA	Additional information	

Sources: (Anderson 2013) (Duna-Dráva Cement Kft. 2009) (Duna-Dráva Cement Kft. 2013) (Duna-Dráva Cement Kft. 2009)

Labatlan	Holcim		
Capacity (Mta cement)	0.5	Technology information	Ball mills used for cement grinding. (Pre-heating other than cyclone preheaters used.)
Kiln type	Wet	Renovation information	Kiln originally built in 1945.
Energy use	>4163 MJ/clinker	Fuel inputs	Coal and petcoke fossil fuel inputs. 16% TSR, 3% SRF, 11% used tires, 1% waste oil, 1% other.
Electricity use	96	Additional information	Holcim has plans to close the plant in 2013.

Sources: (Anderson 2013) (Holcim Hungary 2010) (Holcim Hungary 2010) (Global cement 2012)

Hejocsaba	Holcim		
Capacity (Mta cement)	1.6	Technology information	
Kiln type	Dry process	Renovation information	Plant closed in 2011. Production lines originally built from 1971-1975.
Energy use		Fuel inputs	
Electricity use		Additional information	The plant had to be closed because of a legal dispute some time before 2010.

Sources: (Anderson 2013) (Perez 2012) (Holcim Hungary 2010) (Holcim 2011)

Királyegyháza	LaFarge		
Capacity (Mta cement)	1.0	Technology information	NA
Kiln type	5-stage PHPC	Renovation information	New plant completed in 2011, with 2500 tpd clinker capacity.
Energy use	NA	Fuel inputs	NA, TSR most likely 0%, but plant has plans to burn alternative fuels.
Electricity use	NA	Additional information	

Sources: (Anderson 2013) (ICR Research 2011) (LAFARGE Cement Magyarország Kft. 2012)

Ireland

Limirick	Irish Cement		
Capacity (Mta cement)	0.8	Technology information	NA
Kiln type	1-stage PH	Renovation information	Dry line completed in 1983 and wet process kilns were taken offline.
Energy use	NA	Fuel inputs	Incinerates petcoke.
Electricity use	NA	Additional information	

Sources: (Irish Cement Ltd. 1991)

Platin	Irish Cement		
Capacity (Mta cement)	2.8	Technology information	Vertical roller mill for cement grinding.
Kiln type	PHPC (based on renovation info) & dry process kiln	Renovation information	New kiln and vertical roller mill installed in 2008. An older dry process kiln from 1977 still in place. Kiln capacity of older kiln approximately 1.0 Mta, dry process kiln.
Energy use	NA	Fuel inputs	0% TSR (Currently applying for permit to incinerate wastes.) Incinerates petcoke.
Electricity use	NA	Additional information	NA

Sources: (Irish Cement Ltd. 2010) (Irish Cement Ltd. 2012)

Kinegad	Lagan		
Capacity (Mta cement)	0.7 Mta	Technology information	NA
Kiln type	PHPC	Renovation information	Plant built in 2002 with 1,800 tpd clinker capacity.
Energy use	NA	Fuel inputs	60% TSR, including MBM, MSW, and waste oils. Incinerates coal.
Electricity use	NA	Additional information	NA

Sources: (Lagan Cement Ltd. 2012) (Lagan Cement Ltd. 2012) (World Cement 2009)

Ballyconnel	Quinn		
Capacity (Mta cement)	1.3	Technology information	NA
Kiln type	PHPC (Assumed from renovation information.)	Renovation information	Plant was built in 2002.
Energy use		Fuel inputs	Received permission to use SMW to cover 55% thermal inputs in 2012. Incinerates coal.
Electricity use		Additional information	The 2 Quinn plants are one mile away from each other, and are one cement works for the company’s purposes.

Sources: (Quinn Cement 2012) (Quinn building products 2012)

Derrylin	Quinn		
Capacity (Mta cement)	0.5	Technology information	NA
Kiln type	PH (Based on renovation information.)	Renovation information	Opened in 1989.
Energy use	NA	Fuel inputs	Received permission to use SMW to cover 55% thermal inputs in 2012. Incinerates coal, most likely hard coal based on given comparison between planned SMW and coal.
Electricity use	NA	Additional information	The 2 Quinn plants are one mile away from each other, and are one cement works for the company’s purposes.

Sources: (Quinn Cement 2012) (Quinn building products 2012)

Latvia

Broceni	Cemex		
Capacity (Mta cement)	1.6	Technology information	Vertical mills for cement grinding.
Kiln type	PHPC (assumed based on renovation information)	Renovation information	New plant commissioned in 2009, replacing old wet works.
Energy use	NA	Fuel inputs	70% alternative fuel inputs. Alternative fuels include Climafuel (RDF from municipal solid waste).
Electricity use	NA	Additional information	NA

Sources: (Cemex 2010) (Cemex Latvia 2012) (Cemex Latvia 2012)

Lithuania

Akmenes	Akmenes Cementas		
Capacity (Mta cement)	1.0	Technology information	NA
Kiln type	Wet type (Currently)	Renovation information	Plant has plans to modernize to 4-stage PHPC 4,500 tpd clinker dry process by the end of 2013. Modernization includes clinker coolers and mills. (New plant will have capacity of around 1.5 Mta cement.)
Energy use	NA	Fuel inputs	10% TSR, consisting of old tires with emissions of 85 t CO_2/TJ. Fossil inputs are coal.
Electricity use	NA	Additional information	NA

Sources: (Akmenes Cementas 2008) (Akmenes Cementas 2008)

Luxembourg

Rumelange	Cimalux		
Capacity (Mta cement)	1.0	Technology information	Satellite cooler, ball mills for cement grinding.
Kiln type	4-stage PH	Renovation information	NA
Energy use	NA	Fuel inputs	25% TSR consisting of tires. Some organic solvents also used.
Electricity use	NA	Additional information	

Sources: (Cemnet 2004) (Perez 2012) (Cimalux 2010)

Esch-sur-Alzette	Cimalux		
Capacity (Mta cement)	0.85	Technology information	Ball mills
Kiln type	none	Renovation information	NA
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Grinding plant

Sources: (Perez 2012) (Cimalux 2010)

Netherlands

Maastricht	ENCI (HeidelbergCement)		
Capacity (Mta cement)	1.4	Technology information	Planetary cooler
Kiln type	2-stage PH	Renovation information	The kiln was constructed in 1968 and reconstructed in 1984 with 0.95 Mta clinker capacity.
Energy use	3.6 GJ/t clinker	Fuel inputs	0.22 GJ Finecokes/t clinker 0.31 GJ PPDF/t clinker 0.13 GJ PPDF 90/t clinker 0.01 GJ paper sludge/t clinker 1.01 GJ anode dust/t clinker 0.23 GJ Glycobottom/t clinker 0.01 GJ natural gas/t clinker 0.29 GJ lignite/t clinker 0.31 GJ animal meal/t clinker 1.2 GJ sewage sludge/t clinker 0.05 GJ paper sludge sappi/t clinker 0.04 GJ natural gas/t clinker 0.07 GJ lignite/t clinker (88% TSR, 41% of which is biomass.)
Electricity use		Additional information	

Source: (Edwards 2012) (EUBIONET3 2009) (Takx 2002)

Rotterdam	ENCI (HeidelbergCement)		
Capacity (Mta cement)	1.15 (Total for ENCI in the Netherlands 3.7)	Technology information	NA
Kiln type	none	Renovation information	NA
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Grinding station

Source: (Perez 2012)

Ijmuiden	ENCI (HeidelbergCement)		
Capacity (Mta cement)	1.15 (Total for ENCI in the Netherlands 3.7)	Technology information	Grinding equipment upgraded in 2004. Ball mills were replaced.
Kiln type	none	Renovation information	NA
Energy use	NA	Fuel inputs	
Electricity use	NA	Additional information	Grinding station, produces blast furnace slag.

Source: (Perez 2012)

Norway

Brevik	Norcem (HeidelbergCement)		
Capacity (Mta cement)	1.5	Technology information	NA
Kiln type	PHPC	Renovation information	NA
Energy use	3670 MJ/t clinker	Fuel inputs	49% TSR, 18% alternative fossil, 31% biomass. Fossil inputs are coal and fuel oil. Has a goal of increasing TSR to 66%.
Electricity use	146 kWh/t cement	Additional information	

Sources: (HeidelbergCement Northern Europe 2009) (Newman 2012)

Kjøpsvik	Norcem (HeidelbergCement)		
Capacity (Mta cement)	0.65	Technology information	NA
Kiln type	PHPC	Renovation information	NA
Energy use	3556 MJ/t clinker	Fuel inputs	27% TSR, 13% alternative fossil, 14% biomass. Alternatives include tires, municipal and commercial waste, and MBM. Coal used as fossil fuel.
Electricity use	148 kWh/t cement	Additional information	Emissions info: 1.45 g NOx/kg clinker 0.34 g SOx/kg clinker 7.56E-2 g PM/kg clinker 4.09E-3 g HCl/kg clinker 2.25E-5 g Hg/kg clinker 2.04E-12 g dioxins/kg clinker

Sources: (HeidelbergCement Northern Europe 2009) (Newman 2012)

Portugal

Secil-Outão	Secil		
Capacity (Mta cement)	3.1 (5.0 for all Secil plants in Portugal)	Technology information	Operates a vertical mill for cement grinding.
Kiln type	Dry process	Renovation information	Wet process was abandoned in 1982 for all Secil plants.
Energy use	NA	Fuel inputs	TSR 22%, 2% biomass and 20% alternative fuels. Fossil fuels include coal, fuel oil, gas, and pet coke. Alternative fossil fuels include tires.
Electricity use	NA	Additional information	Produces grey and white cement.

Sources: (Secil 2007) (Secil 2011) (Germendi 2013) (Germendi 2013)

Pataias	Secil		
Capacity (Mta cement)	0.4	Technology information	NA
Kiln type	Dry process	Renovation information	Wet process was abandoned in 1982 for all Secil plants.
Energy use	NA	Fuel inputs	TSR 22%, 2% biomass and 20% alternative fuels. Fossil fuels include coal, fuel oil, gas, and pet coke. Alternative fossil fuels include tires.
Electricity use	NA	Additional information	Produces grey and white cement.

Sources: (Secil 2007) (Secil 2011) (Germendi 2013)

Maceira-Liz	Secil		
Capacity (Mta cement)	1.5	Technology information	NA
Kiln type	PH	Renovation information	Current lines were remodeled in 1986.
Energy use	NA	Fuel inputs	TSR 22%, 2% biomass and 20% alternative fuels. Fossil fuels include coal, fuel oil, gas, and pet coke. Alternative fossil fuels include tires.
Electricity use	NA	Additional information	Produces grey and white cement.

Sources: (Secil 2012) (Secil 2011) (Germendi 2013)

Alhandra	CIMPOR		
Capacity (Mta cement)	7.0 (for all CIMPOR plants in Portugal)	Technology information	NA
Kiln type	PH	Renovation information	NA
Energy use	NA	Fuel inputs	10% TSR, mostly tires.
Electricity use	NA	Additional information	

Sources: (Cimpor 2011) (Germendi 2013)

Loule	CIMPOR		
Capacity (Mta cement)	7.0 (for all CIMPOR plants in Portugal)	Technology information	NA
Kiln type	PH	Renovation information	NA
Energy use	NA	Fuel inputs	10% TSR, mostly tires.
Electricity use	NA	Additional information	

Sources: (Cimpor 2011) (Germendi 2013)

Souselas	CIMPOR		
Capacity (Mta cement)	7.0 (for all CIMPOR plants in Portugal)	Technology information	NA
Kiln type	PH	Renovation information	NA
Energy use	NA	Fuel inputs	10% TSR, mostly tires.
Electricity use	NA	Additional information	

Sources: (Cimpor 2011) (Germendi 2013)

Romania

Bicaz	HeidelbergCement		
Capacity (Mta cement)	3.0	Technology information	New bag filter installed in 2009.
Kiln type	New line most likely PHPC. Old line unknown	Renovation information	Capacity increased by 1.4 Mta in 2009. 1st production line dates back to 1975. New clinker cooler was installed in line 2 in 2009.
Energy use		Fuel inputs	TSR unknown. Incinerates tires, plastics, impregnated sawdust, and wood waste.
Electricity use		Additional information	

Sources: (Perez 2012) (World Cement 2009) (HeidelbergCement Romania 2009) (HeidelbergCement Romania 2009)

Deva	HeidelbergCement		
Capacity (Mta cement)	1.25	Technology information	Grate cooler
Kiln type	PH	Renovation information	Came into operation in 1976. Preheater upgraded in 2000.
Energy use		Fuel inputs	TSR unknown. Incinerates tires, plastics, impregnated sawdust.
Electricity use		Additional information	Emissions info: 0.4 kg dust/t clinker 1.37 kg NOx/t clinker (787.5 mg/Nm3) 0.24 kg SO2/t clinker (106.21 mg/Nm3) 1.26 kg CO/t clinker

Sources: (Perez 2012) (HeidelbergCement Romania 2011) (HeidelbergCement Romania 2009) (Ceprocim Engineering S.R.L. 2000)

Fieni	HeidelbergCement		
Capacity (Mta cement)	1.8	Technology information	Grate cooler
Kiln type	4-stage PH	Renovation information	Replaced electrostatic precipitator in 2002. Plant originally established in 1914. Preheater of production line 7 upgraded in 2000 to 4,000 tpd. (Appears to be only one line.)
Energy use		Fuel inputs	TSR unknown. Incinerates tires, plastics, waste oils, solvents, and impregnated sawdust. Coal and petcoke are fossil inputs.
Electricity use	120 kWh/t cement	Additional information	

Sources: (Perez 2012) (HeidelbergCement Romania 2009) (HeidelbergCement Romania 2009) (Ceprocim engineering S.R.L. 2002)

Campulung	Holcim		
Capacity (Mta cement)	2.0	Technology information	
Kiln type	5-stage PHPC & DL	Renovation information	Plant expanded in 2008 to add 4,000 tpd kiln line, increasing total cement capacity by 1 Mta, and replacing three smaller obsolete kilns. New vertical cement grinding mill installed in 2009. The plant was originally built in 1971 with long dry kilns.
Energy use	NA	Fuel inputs	19.5% TSR
Electricity use	100 kWh/t cement	Additional information	

Sources: (Perez 2012) (Brininstool 2010) (Cemnet 2008) (Holcim Romania 2010) (Romania 2010) (Holcim (Romania) SA 2002)

Turda	Holcim		
Capacity (Mta cement)	0.4	Technology information	NA
Kiln type	none	Renovation information	Turda was converted into a grinding plant around 2005. It had previously been the only wet process plant in Romania.
Energy use	NA	Fuel inputs	NA
Electricity use	NA	Additional information	Grinding plant

Sources: (Perez 2012) (Hargreaves 2003) (Flammer 2012)

Alesd	Holcim		
Capacity (Mta cement)	3.3	Technology information	Employs 4 kilns. Employs waste heat recovery as of 2012, to reduce electricity consumption by 15%.
Kiln type	PHPC, other kiln lines unkonwn	Renovation information	One dry kiln upgraded with preheating and precalcining by 2009 to a capacity of 4,300 tpd. Older lines were commissioned in 1970, either DL or SW/SD.
Energy use	2.7 MJ/t cement (clinker factor unknown)	Fuel inputs	19.5% TSR, incinerates waste oil, tires, and SRF.
Electricity use	100 kWh/t cement	Additional information	

Sources: (Perez 2012) (Holcim Romania 2010) (Ceprocim Engineering S.R.L. 2009) (Romania 2010)

Hoghiz	LaFarge		
Capacity (Mta cement)	1.6	Technology information	Grate cooler
Kiln type	4-stage PH, other possible lines unknown.	Renovation information	Preheater for kiln modernized in 1999, but modernization not extensive, no capacity increase. (Most likely more than one kiln.) Kiln built in 1970s.
Energy use		Fuel inputs	Combusts alternative fuels. No information on how much or what.
Electricity use		Additional information	

Sources: (Perez 2012) (Ceprocim Engineering S.R.L. 1999)

Medgidia	LaFarge		
Capacity (Mta cement)	3.0	Technology information	Cement grinding facilities replaced in 2009 with vertical roller mill system.
Kiln type	3-stage PH	Renovation information	Preheater renovated for lines 10 & 11 in 2000. Renovation not extensive, no capacity increase.
Energy use	NA	Fuel inputs	Combusts alternative fuels. No information on how much or what. Incinerates coal and petcoke.
Electricity use	NA	Additional information	

Sources: (Perez 2012) (Ceprocim Engineering S.R.L. 2000) (World Cement 2009)

Slovakia

Rohožník	Holcim		
Capacity (Mta cement)	2.2	Technology information	Bag filter. Planetary cooler.
Kiln type	5-stage PHPC	Renovation information	Plant has two production lines. Rotary kiln was modernized in 2003. Modernized kiln handles grey production.
Energy use	3,489 MJ/t clinker (grey) 6,780 MJ/t clinker (white)	Fuel inputs	Grey cement: 21% Coal 11% Petcoke 0.5% Natural gas Alternative fuels 67.5% White cement: 51% Petcoke 20.7% Natural gas 28.3% Alternative fuels
Electricity use	109.3 kWh/t grey cement 154.8 kWh/t white cement	Additional information	Produces grey and white cement. (White cement most likely produced with wet process.) Sold 0.12 MT white cement in 2010. Wet kiln capcity assumed to be 0.4 Mta based on CEMBUREAU's database. Clinker factor of grey cement 78.3%. Clinker factor of white cement 92.8%

Sources: (Perez 2012) (CEMBUREAU 2002) (Holcim (Slovensko) a.s. 2010) (Holcim (Slovensko) a.s. 2010) (Holcim (Slovensko) a.s. 2010) (World Cement 2004)

Turňa	Holcim		
Capacity (Mta cement)	1.3	Technology information	NA
Kiln type	5-stage PHPC	Renovation information	Modernized in 2005, added preheater and precalciner. Increased kiln capacity from 2000 to 2350 tpd.
Energy use	3,489 MJ/t clinker (grey)	Fuel inputs	21% Coal 11% Petcoke 0.5% Natural gas Alternative fuels 67.5%
Electricity use	109.3 kWh/t grey cement	Additional information	Clinker factor of grey cement 78.3%.

Sources: (Perez 2012) (Holcim (Slovensko) a.s. 2008) (Holcim (Slovensko) a.s. 2010) (World Cement 2006)

Považska	PCLA (Berger Holding company)		
Capacity (Mta cement)	1.05	Technology information	Cement grinding plant modernized in 2004 with a ball mill and separating circuit.
Kiln type	PH	Renovation information	Rotary kiln modernized in 2006. Preheater rebuilt, increasing capacity kiln to 2400.
Energy use	NA	Fuel inputs	54% coal, 10% MBM, 4% waste tires, 32% RFD.
Electricity use	NA	Additional information	

Sources: (Považská cementáreň 2010) (Považská cementáreň 2011) (World Cement 2004)

Horne Srnie	Cemmac		
Capacity (Mta cement)	0.6	Technology information	Ball mills for cement grinding
Kiln type	5-stage PHPC	Renovation information	Newest kiln lines built in 1988.
Energy use	NA	Fuel inputs	Incinerates coal, natural gas, RDF, and tires
Electricity use	NA	Additional information	Emissions: 8.9 mg PM/Nm3 6.4 mg SOx/Nm3 787 mg NOx/Nm3 23.8 mg TOC/Nm3 3518 mg CO/Nm3

Sources: (Cemmac 2011) (Cemmac 2011)

Slovenia

Anhovo	Salonit Anhovo		
Capacity (Mta cement)	1.1	Technology information	Uses chamber ball mills for cement grinding
Kiln type	PHPC	Renovation information	Plant was modernized in 2009.
Energy use	3.2 MJ/t clinker (acheived)	Fuel inputs	TSR% not given. Tires are used for the precalciner.
Electricity use	NA	Additional information	

Sources: (Brininstool 2011) (Salonit Anhovo 2012) (Salonit Anhovo 2009)

Trbovlje	LaFarge		
Capacity (Mta cement)	0.6	Technology information	Ball mills for cement grinding
Kiln type	4 stage PH	Renovation information	Latest kiln from 1980. New device for treating NOx emissions started in 2008.
Energy use	NA	Fuel inputs	TSR% not given. Approximately 7,000 tons of alternative fuels are burned per year including tires, waste oils, and plastics, but their permit for incinerating fuels is currently in contention.
Electricity use	NA	Additional information	

Sources: (Brininstool 2011) (LaFarge Cement 2013) (LaFarge Cement 2012)

Sweden

Degerhamn, Skovde, and Slite Plants	Cementa AB (HeidelbergCement)		
Capacity (Mta cement)	3.4	Technology information	NA
Kiln type	PHPC	Renovation information	The plants were renovated between 1993-2000.
Energy use	NA	Fuel inputs	30% TSR, including tires, MBM, and plastics. Fossil fuel inputs include coal and fuel oil.
Electricity use		Additional information	Produces grey and white cement.

Sources: (Newmand 2012) (Cementa 2009)

Switzerland

Siggenthal	Holcim cement		
Capacity (Mta cement)	1.26 (3.6 for all of Holcim Switzerland)	Technology information	NA
Kiln type	PHPC	Renovation information	NA
Energy use	~3.2 MJ/kg clinker	Fuel inputs	>35% TSR. Fuels include dried sludge, tires, MBM, plastics, and solvents.
Electricity use	98 kWh/t cement	Additional information	

Sources: (Holcim (Suisse) SA 2011) (Holcim (Schweiz) SA 2010)

Untervaz	Holcim cement		
Capacity (Mta cement)	1.26	Technology information	Uses a waste heat recovery system.
Kiln type	PHPC	Renovation information	NA
Energy use	~3.5 MJ/kg clinker	Fuel inputs	>40% TSR, including dried sludge and plastics.
Electricity use	93.75 kWh/t cement	Additional information	

Sources: (Holcim (Suisse) SA 2011) (Holcim (Schweiz) AG 2010) (World Cement 2009)

Eclepens	Holcim cement		
Capacity (Mta cement)	1.08	Technology information	NA
Kiln type	PHPC	Renovation information	NA
Energy use	~3 MJ/kg clinker	Fuel inputs	>50% TSR. Including tires, sewage sludge, solvents, plastics.
Electricity use	83.3 kWh/t cement	Additional information	

Sources: (Holcim (Suisse) SA 2011) (Holcim (Suisse) SA 2010)

Reuchenette	Ciments Vigier (Vicat)		
Capacity (Mta cement)	0.75	Technology information	NA
Kiln type	PHPC	Renovation information	NA
Energy use	NA	Fuel inputs	60% TSR, including waste oil, solvents, and sewage sludge.
Electricity use	NA	Additional information	

Sources: (Ciments Vigier SA 2010)

Wildegg	Jura		
Capacity (Mta cement)	0.78	Technology information	NA
Kiln type	4-stage PH	Renovation information	The current kiln built in 1986.
Energy use	NA	Fuel inputs	70% TSR, including tires, plastic wastes, dried sewage sludge, MBM, waste oils, solvents, and paper materials.
Electricity use		Additional information	

Sources: (Jura Cement 2011) (Jura Cement 2012)

Cornaux	Jura		
Capacity (Mta cement)	0.3	Technology information	NA
Kiln type	SD	Renovation information	Plant commissioned in 1966.
Energy use	NA	Fuel inputs	70% TSR, including tires, plastic wastes, dried sewage sludge, MBM, waste oils, solvents, and paper materials.
Electricity use	NA	Additional information	

Sources: (Jura Cement 2012) (Jura Cement 2011)

Appendix B GNR and clinker production ata

The below tables are a compilation of data taken from the GNR database (Klee, Hunziker et al. 2011) used in this analysis. Data was used for the year 2010, the most recent for which data is available.

Table 18: Share of EU clinker produced in each country

	Share of production of clinker produced in EU-27 (GNR, 2010)	**Share of production of cement production in EU (USGS, 2010)**	**Share of production of clinker in EU, adjusting for clinker share of GNR countries**
Austria	0.022	0.022	0.022
Belgium		0.042	0.039
Bulgaria		0.010	0.009
Cyprus		0.007	0.006
Czech Republic	0.015	0.017	0.015
Denmark		0.008	0.008
Estonia		0.002	0.002
Finland		0.006	0.006
France	0.103	0.091	0.103
Germany	0.175	0.152	0.175
Greece		0.046	0.043
Hungary		0.013	0.012
Ireland		0.012	0.011
Italy	0.168	0.175	0.168
Latvia		0.006	0.005
Lithuania		0.004	0.004
Luxembourg		0.005	0.005
Netherlands		0.014	0.013
Malta		0	0.000
Poland	0.084	0.080	0.084
Portugal		0.037	0.034
Romania		0.036	0.033
Slovakia		0.015	0.014
Slovenia		0.005	0.005
Spain	0.124	0.133	0.124
Sweden		0.013	0.012
United Kingdom	0.049	0.051	0.049

Table 19: Clinker factor of GNR countries and remaining countries in the EU

Clinker factor	**Mass fraction of cement consisting of clinker (%)**
EU-27	73.7
Austria	70.4
Czech Republic	77.2
France	74.1
Germany	68.1
Italy	74.4
Spain	81.2
Poland	72.8
UK	73.3
CF for non-GNR countries	73.7

The clinker factor of non-GNR countries is the calculated using the average clinker factor for EU-27, and subtracting the contribution of clinker factor from each GNR country using each country's known clinker factor and its share of total clinker production.

Table 20: Kiln technology distribution of EU and GNR countries

	PHPC	**PH**	**DL**	**SD/SW**	**W**
EU 27 (Based on GNR data and EU tech distribution given in (Pardo, Moya et al. 2011)	0.495	0.305	0.060	0.100	0.040
Austria	0.013	0.009	0	0	0
France	0.037	0.032	0	0.034	0
Germany	0.058	0.107	0	0.011	0
Italy	0.102	0.020	0.013	0.026	0
Poland	0.050	0.033	0	0	0
Spain	0.083	0.041	0	0	0
United Kingdom	0.049	0	0	0	0

Fuel mixes of GNR countries

The following tables show the percentage of thermal inputs of each type of fuel per unit clinker of each GNR country.

Table 21: Fuel inputs per unit clinker produced in Austria

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	55.5 %	Fraction of thermal energy	7.55 %	Fraction of thermal energy	36.85 %
Distribution of individual fuels					

Waste oil	6 %	Dried sewage sludge	19.7 %	Coal, anthracite, waste coal	52.2 %
Tires	11 %	Wood, non-impregnated saw dust	0	Lignite	21.7 %
Plastics	74.5 %	Paper. carton	0.6 %	Petcoke	15.6 %
Solvents	4.3 %	Animal meal	36.2 %	Shale	0
Impregnated saw dust	0.2 %	Agricultural. Organic, diaper waste, charcoal	1.1 %	(ultra) Heavy fuel	7.6 %
Mixed industrial waste	0	Other biomass	42.4 %	Diesel oil	0.5 %
Other fossil based wastes	4 %			Natural gas	2.4 %

Table 22: Fuel inputs per unit clinker produced in the Czech Republic

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	49 %	Fraction of thermal energy	5 %	Fraction of thermal energy	46 %
Distribution of individual fuels					
Waste oil	0.9 %	Dried sewage sludge	5.7 %	Coal, anthracite, waste coal	97.2 %
Tires	17.7 %	Wood, non-impregnated saw dust	0	Lignite	0
Plastics	17.4 %	Paper. carton	0	Petcoke	0
Solvents	4.8 %	Animal meal	42.6 %	Shale	0
Impregnated saw dust	22.3 %	Agricultural. Organic, diaper waste, charcoal	0	(ultra) Heavy fuel	0.4 %
Mixed industrial waste	27.3 %	Other biomass	51.7 %	Diesel oil	1.5 %
Other fossil based wastes	9.6 %			Natural gas	0.9 %

Table 23: Fuel inputs per unit clinker produced in France

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	20.8 %	Fraction of thermal energy	8.63 %	Fraction of thermal energy	70.5 %
Distribution of individual fuels					
Waste oil	13.1 %	Dried sewage sludge	2.9 %	Coal, anthracite, waste coal	34.6 %
Tires	21.1 %	Wood, non-impregnated saw dust	1.6 %	Lignite	0
Plastics	6.9 %	Paper. carton	0.3 %	Petcoke	50.6 %
Solvents	23.4 %	Animal meal	80.8 %	Shale	0
Impregnated saw dust	17.8 %	Agricultural. Organic, diaper waste, charcoal	5.6 %	(ultra) Heavy fuel	12.7 %
Mixed industrial	4.3 %	Other biomass	8.8 %	Diesel oil	1.7 %

waste					
Other fossil based wastes	13.4 %			Natural gas	0.5 %

Table 24: Fuel inputs per unit clinker produced in Germany

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	55.6 %	Fraction of thermal energy	6.1 %	Fraction of thermal energy	38.3 %
Distribution of individual fuels					
Waste oil	2.6 %	Dried sewage sludge	20.3 %	Coal, anthracite, waste coal	35.3 %
Tires	14.7 %	Wood, non-impregnated saw dust	2 %	Lignite	53.9 %
Plastics	31.3 %	Paper. carton	9.8 %	Petcoke	9 %
Solvents	5.1 %	Animal meal	67.6 %	Shale	0
Impregnated saw dust	0.9 %	Agricultural. Organic, diaper waste, charcoal	0	(ultra) Heavy fuel	1 %
Mixed industrial waste	39.9 %	Other biomass	0.3 %	Diesel oil	0.6 %
Other fossil based wastes	5.5 %			Natural gas	0.2 %

Table 25: Fuel inputs per unit clinker produced in Italy

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	10.8 %	Fraction of thermal energy	4.6 %	Fraction of thermal energy	84.6 %
Distribution of individual fuels					
Waste oil	5.2 %	Dried sewage sludge	17.4 %	Coal, anthracite, waste coal	1.3 %
Tires	39.4 %	Wood, non-impregnated saw dust	41 %	Lignite	0
Plastics	7.9 %	Paper. carton	0.4 %	Petcoke	96.7 %
Solvents	11.3 %	Animal meal	25.3 %	Shale	0.5 %
Impregnated saw dust	5.8 %	Agricultural. Organic, diaper waste, charcoal	5.9 %	(ultra) Heavy fuel	0.8 %
Mixed industrial waste	25 %	Other biomass	10 %	Diesel oil	0.2 %
Other fossil based wastes	5.4 %			Natural gas	0.5 %

Table 26: Fuel inputs per unit clinker produced in Poland

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	30.9 %	Fraction of thermal energy	8.7 %	Fraction of thermal energy	60.4 %
Distribution of individual fuels					

Waste oil	0.1 %	Dried sewage sludge	4.9 %	Coal, anthracite, waste coal	93.1 %
Tires	35.7 %	Wood, non-impregnated saw dust	0.4 %	Lignite	0
Plastics	0.7 %	Paper. carton	0	Petcoke	5.5 %
Solvents	20.4	Animal meal	71.2 %	Shale	0
Impregnated saw dust	0	Agricultural. Organic, diaper waste, charcoal	0	(ultra) Heavy fuel	0
Mixed industrial waste	34.8 %	Other biomass	23.5 %	Diesel oil	1.3 %
Other fossil based wastes	8.3 %			Natural gas	0.1 %

Table 27: Fuel inputs per unit clinker produced in Spain

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	10.8 %	Fraction of thermal energy	4.6 %	Fraction of thermal energy	84.6 %
Distribution of individual fuels					
Waste oil	5.20 %	Dried sewage sludge	17.40 %	Coal, anthracite, waste coal	0.13 %
Tires	39.40 %	Wood, non-impregnated saw dust	41.10 %	Lignite	0.00 %
Plastics	7.90 %	Paper. carton	0.40 %	Petcoke	9.77 %
Solvents	11.30 %	Animal meal	25.30 %	Shale	0.00 %
Impregnated saw dust	5.80 %	Agricultural. Organic, diaper waste, charcoal	5.90 %	(ultra) Heavy fuel	0.08 %
Mixed industrial waste	25.00 %	Other biomass	10.00 %	Diesel oil	0.02 %
Other fossil based wastes	5.40 %			Natural gas	0.00 %

Table 28: Fuel inputs per unit clinker produced in the UK

Fossil fuel wastes		**Biomass**		**Fossil fuels**	
Fraction of thermal energy	30.9 %	Fraction of thermal energy	8.61 %	Fraction of thermal energy	60.49 %
Distribution of individual fuels					
Waste oil	0.10 %	Dried sewage sludge	4.90 %	Coal, anthracite, waste coal	93.10 %
Tires	35.70 %	Wood, non-impregnated saw dust	0.40 %	Lignite	0.00 %
Plastics	0.70 %	Paper. carton	0.00 %	Petcoke	5.50 %
Solvents	20.40 %	Animal meal	71.20 %	Shale	0.00 %
Impregnated saw dust	0 %	Agricultural. Organic, diaper waste, charcoal	0 %	(ultra) Heavy fuel	0.00 %
Mixed industrial	34.70 %	Other biomass	23.50 %	Diesel oil	1.30 %

waste					
Other fossil based wastes	8.30 %			Natural gas	0.10 %

Appendix C Cement consumption, GDP, and population data

Table 29: Historical cement consumption (kg/person) (CEMBUREAU 2010)

Belgium	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Bulgaria	598	558	535	527	552	555	575	562	565	514	534
Czech Republic	179	178	207	250	308	399	482	554	631	400	313
Denmark	351	352	361	397	442	432	469	500	499	391	351
Germany	293	280	297	283	296	304	332	342	339	290	NA
Estonia	435	379	351	363	353	328	351	332	336	308	301
Ireland	179	192	239	277	311	378	466	491	340	189	201
Greece	835	826	790	858	1111	1118	1117	1114	803	427	316
Spain	832	872	970	1013	963	910	1045	988	913	699	NA
France	960	1041	1077	1109	1134	1174	1277	1259	943	631	533
Italy	351	349	347	344	363	369	392	401	388	326	315
Cyprus	674	693	724	759	801	788	798	784	701	601	562
Latvia	1369	1515	1705	1825	2202	2125	2125	2301	2496	1807	1610
Lithuania	114	120	141	149	191	260	335	392	258	137	129
Luxembourg	122	122	144	171	198	234	295	310	295	161	179
Hungary	1227	1232	1243	1213	1215	1166	1219	1241	1228	1076	894
Malta	348	346	377	395	397	411	426	397	399	321	251
Netherlands	663	667	699	687	700	829	970	880	919	798	688
Austria*	394	360	335	319	322	330	354	360	377	325	287
Poland	562	553	575	560	567	649	676	693	714	603	570
Portugal	375	300	296	291	301	318	380	440	449	402	410
Romania	1090	1105	1046	889	878	830	741	738	690	580	546
Slovenia	192	193	219	226	264	291	366	453	517	377	332
Slovak Republic	622	591	582	671	631	676	703	802	780	590	513
Finland	312	311	327	331	356	422	430	464	475	333	350
Sweden	330	310	300	306	319	327	360	387	361	253	336
United Kingdom	173	183	176	181	192	210	236	258	273	210	229
Norway	227	222	224	227	232	228	229	237	203	154	158
Switzerland	284	275	278	282	324	381	389	436	420	331	342
Belgium	693	651	638	622	619	615	561	527	528	542	498

Table 30: Future projections of GDP in Europe (European Commission 2012)

GDP (M€ 2010)	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**
Belgium	352	390	419	450	486	529	577	629	685	745	812
Bulgaria	36	42	46	49	53	57	60	64	66	69	73
Czech Republic	145	163	180	196	214	232	250	268	283	299	317
Denmark	234	255	271	293	316	339	365	397	432	468	505
Germany	2499	2738	2886	3003	3088	3167	3281	3427	3570	3709	3854
Estonia	15	17	19	21	23	25	28	29	31	32	34
Ireland	154	165	189	222	258	290	319	347	380	422	473
Greece	230	231	249	263	281	300	317	333	353	376	403
Spain	1063	1163	1284	1461	1657	1804	1921	2023	2140	2291	2471
France	1948	2177	2391	2631	2859	3092	3351	3630	3923	4243	4597
Italy	1549	1648	1769	1939	2099	2237	2373	2520	2701	2909	3129
Cyprus	18	19	21	23	25	29	32	35	38	41	44
Latvia	18	20	22	25	28	30	32	34	34	35	36
Lithuania	27	32	34	37	40	44	47	51	53	55	57
Luxembourg	42	50	56	62	67	74	80	87	95	103	112
Hungary	98	106	112	122	134	145	154	163	171	178	186
Malta	6	7	8	8	9	10	11	11	12	12	13
Netherlands	592	652	700	741	781	826	882	944	1012	1082	1155
Austria	284	313	339	363	387	414	444	476	509	543	579
Poland	354	429	482	526	568	611	650	680	702	720	741
Portugal	173	172	182	199	219	238	255	272	288	304	321
Romania	122	140	151	160	171	182	193	201	207	212	218
Slovenia	36	41	45	49	52	56	59	62	65	68	72
Slovakia	66	78	91	103	114	122	129	133	138	142	148
Finland	180	206	226	243	260	280	303	327	352	377	405
Sweden	346	389	427	467	509	556	608	665	723	780	844

United Kingdom	1695	1928	2152	2370	2600	2857	3153	3477	3808	4149	4523
Norway	243	275	307	337	369	403	441	484	529	577	629
Switzerland	385	504	564	633	710	789	876	973	1081	1201	1334

Table 31: Future population projections of European countries (Eurostat 2013)

	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Belgium	1.08E+07	1.12E+07	1.16E+07	1.19E+07	1.22E+07	1.25E+07	1.27E+07	1.29E+07	1.31E+07	1.33E+07	1.34E+07
Bulgaria	7.56E+06	7.36E+06	7.12E+06	6.86E+06	6.61E+06	6.41E+06	6.24E+06	6.07E+06	5.90E+06	5.72E+06	5.53E+06
Czech Republic	1.05E+07	1.07E+07	1.08E+07	1.09E+07	1.08E+07	1.08E+07	1.07E+07	1.07E+07	1.07E+07	1.06E+07	1.05E+07
Denmark	5.53E+06	5.63E+06	5.72E+06	5.81E+06	5.89E+06	5.95E+06	5.99E+06	6.02E+06	6.04E+06	6.06E+06	6.08E+06
Germany	8.17E+07	8.10E+07	8.01E+07	7.91E+07	7.79E+07	7.65E+07	7.48E+07	7.29E+07	7.08E+07	6.86E+07	6.64E+07
Estonia	1.34E+06	1.34E+06	1.32E+06	1.30E+06	1.28E+06	1.26E+06	1.24E+06	1.23E+06	1.21E+06	1.20E+06	1.17E+06
Ireland	4.47E+06	4.61E+06	4.81E+06	5.05E+06	5.28E+06	5.51E+06	5.76E+06	6.00E+06	6.21E+06	6.39E+06	6.54E+06
Greece	1.13E+07	1.14E+07	1.15E+07	1.16E+07	1.16E+07	1.16E+07	1.16E+07	1.16E+07	1.16E+07	1.15E+07	1.13E+07
Spain	4.60E+07	4.69E+07	4.80E+07	4.90E+07	5.00E+07	5.09E+07	5.17E+07	5.24E+07	5.27E+07	5.26E+07	5.23E+07
France	6.47E+07	6.64E+07	6.78E+07	6.91E+07	7.03E+07	7.13E+07	7.22E+07	7.28E+07	7.32E+07	7.35E+07	7.37E+07
Italy	6.03E+07	6.18E+07	6.29E+07	6.37E+07	6.45E+07	6.52E+07	6.57E+07	6.60E+07	6.59E+07	6.56E+07	6.50E+07
Cyprus	8.03E+05	8.39E+05	8.85E+05	9.33E+05	9.73E+05	1.01E+06	1.04E+06	1.06E+06	1.09E+06	1.11E+06	1.13E+06
Latvia	2.25E+06	2.19E+06	2.14E+06	2.08E+06	2.02E+06	1.96E+06	1.91E+06	1.85E+06	1.80E+06	1.74E+06	1.67E+06
Lithuania	3.33E+06	3.25E+06	3.18E+06	3.11E+06	3.04E+06	2.98E+06	2.92E+06	2.87E+06	2.81E+06	2.75E+06	2.68E+06
Luxembourg	5.02E+05	5.41E+05	5.73E+05	6.00E+05	6.26E+05	6.49E+05	6.70E+05	6.88E+05	7.04E+05	7.17E+05	7.28E+05

Hungary	1.00E+07	9.96E+06	9.90E+06	9.82E+06	9.70E+06	9.57E+06	9.44E+06	9.32E+06	9.18E+06	9.03E+06	8.86E+06
Malta	4.13E+05	4.13E+05	4.15E+05	4.18E+05	4.17E+05	4.13E+05	4.08E+05	4.02E+05	3.97E+05	3.92E+05	3.87E+05
Netherlands	1.66E+07	1.70E+07	1.72E+07	1.74E+07	1.76E+07	1.77E+07	1.76E+07	1.75E+07	1.74E+07	1.72E+07	1.71E+07
Austria	8.38E+06	8.47E+06	8.59E+06	8.73E+06	8.85E+06	8.93E+06	8.98E+06	8.99E+06	8.97E+06	8.92E+06	8.87E+06
Poland	3.82E+07	3.84E+07	3.84E+07	3.81E+07	3.76E+07	3.69E+07	3.61E+07	3.53E+07	3.45E+07	3.37E+07	3.27E+07
Portugal	1.06E+07	1.07E+07	1.07E+07	1.08E+07	1.08E+07	1.08E+07	1.08E+07	1.07E+07	1.06E+07	1.04E+07	1.03E+07
Romania	2.15E+07	2.13E+07	2.10E+07	2.07E+07	2.03E+07	1.99E+07	1.94E+07	1.90E+07	1.85E+07	1.79E+07	1.73E+07
Slovenia	2.05E+06	2.11E+06	2.14E+06	2.15E+06	2.15E+06	2.15E+06	2.14E+06	2.13E+06	2.11E+06	2.09E+06	2.06E+06
Slovakia	5.42E+06	5.51E+06	5.58E+06	5.60E+06	5.58E+06	5.53E+06	5.47E+06	5.40E+06	5.33E+06	5.23E+06	5.12E+06
Finland	5.35E+06	5.47E+06	5.58E+06	5.65E+06	5.70E+06	5.73E+06	5.73E+06	5.72E+06	5.73E+06	5.73E+06	5.74E+06
Sweden	9.34E+06	9.73E+06	1.01E+07	1.04E+07	1.06E+07	1.07E+07	1.09E+07	1.11E+07	1.12E+07	1.14E+07	1.15E+07
United Kingdom	6.20E+07	6.41E+07	6.63E+07	6.84E+07	7.02E+07	7.19E+07	7.34E+07	7.50E+07	7.64E+07	7.77E+07	7.89E+07
Norway	4.86E+06	5.14E+06	5.38E+06	5.59E+06	5.79E+06	5.95E+06	6.10E+06	6.24E+06	6.37E+06	6.48E+06	6.59E+06
Switzerland	7.79E+06	8.19E+06	8.51E+06	8.75E+06	8.94E+06	9.09E+06	9.19E+06	9.26E+06	9.31E+06	9.33E+06	9.32E+06

Appendix D Background data for the CCS life cycle inventory

Table 32: Distribution of capital costs for industrial plants (Nguyen 1980)

Type of commodity	Share of capital costs	EXIOPOL sector
Equipment	0.23	74, Manufacture of machinery and equipment
Equipment installation	0.1	74, Manufacture of machinery and equipment
Process piping	0.18	72, Manufacture of fabricated metal products, except machinery and equipment (28)
Electrical	0.03	76, manufacture of electrical machinery and apparatuses
Instrumentation	0.05	76, manufacture of electrical machinery and apparatuses
Process building	0.03	95, construction
Auxiliary building	0.14	95, construction
Plant services	0.07	95, construction
Site improvement	0.035	95, construction
Field expenses	0.025	112, real estate activities
Project management	0.11	115, research and development

Appendix E Price and valuation information of commodities

For the purposes of the model, it is assumed that the cement industry receives alternative fuels in the form of waste for free. Their price is therefore 0 €/kg.

Table 33: Prices of fuels and cement in basic price valuation in 2000 Euros

Fuel type	€ (2000)/kg
Coal, anthracite, waste coal	0.068
Lignite	0.055
Petcoke	0.034
Shale	0.005
(ultra) Heavy fuel	0.097
Diesel oil	0.637
Natural gas	0.299
Waste oil	0
Tires	0
Plastics	0
Solvents	0
Impregnated sawdust	0

Mixed industry wastes	0
Other fossil based wastes	0
MSW	0
Dried sewage sludge	0
wood, non-impregnated saw dust	0
Paper, carton	0
Animal meal	0
Agricultural, organic, diaper waste, charcoal	0
Other biomass	0
Cement	0.046

Converting from purchaser prices, the valuation of prices found in literature to basic prices was done by calculating the difference in purchaser and basic prices given the Supply and Use table table for France, available in Eurostat. No Supply and Use tables (SUT) showing the differences in price valuation for Europe and a whole were available, so the SUT for France was chosen because it is one of Europe's biggest economies.

To determine the basic price of a commodity once its price had been adjusted for inflation to 2000 Euro values, the ratios given in Table 28 applied to find the basic price of the commodity.

Table 34: Ratio of basic to purchaser price valuations given in the French SUT for commodities relevant to the no CCS and CCS cases

Diff between purchaser and basic prices (basic price/purchaser price)	Sector name in SUT	EXIOPOL sector name, used in inventories
0.9973	Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
2.0212	Land transport; transport via pipeline services	Transport via pipelines
0.8103	Machinery and equipment n.e.c.	Manufacture of machinery and equipment n.e.c. (29)
0.8647	Fabricated metal products, except machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment (28)
0.9748	Electrical machinery and apparatus n.e.c.	Manufacture of electrical machinery and apparatus n.e.c. (31)
0.9158	Construction work	Construction (45)
0.9851	Real estate services	Real estate activities (70)
0.9431	Other business services	Other business activities
0.8932	Electrical energy, gas, steam and hot water	Production of electricity by gas
0.9978	Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	Extraction of natural gas and services related to natural gas extraction, excluding surveying
0.8649	Insurance and pension funding services, except compulsory social security services	Insurance and pension funding, except compulsory social security (66)
0.7736	Chemicals, chemical products and man-made fibres	Manufacture of chemicals and chemical products (24)
0.9403	Collected and purified water, distribution services of water	Collection, purification and distribution of water (41)
0.8217	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)
0.9918	Research and development services	Research and development (73)
0.9041	Other services	Other service activities (93)
0.8825	Coal and lignite; peat	Mining of coal and lignite; extraction of peat (10)
0.6025	Coke, refined petroleum products and nuclear fuels	Manufacture of motor spirit (gasoline)
0.6025	Coke, refined petroleum products and nuclear fuels	Manufacture of fuel oils n.e.c.
0.6025	Coke, refined petroleum products and nuclear fuels	Manufacture of other petroleum products

Appendix F Correspondence matrix for the 9x9 to 44x44 MRIOT frameworks

Table 35: Matrix showing which of the 9 global regions the 44 countries belong to

2-Letter Country Code	China	India	OECD Europe	OECD North America	OECD Pacific	Economies in transition	Latin America	Other developing Asia	Africa and Middle East
AT	0	0	1	0	0	0	0	0	0
BE	0	0	1	0	0	0	0	0	0
BG	0	0	0	0	0	1	0	0	0
CY	0	0	0	0	0	1	0	0	0
CZ	0	0	1	0	0	0	0	0	0
DE	0	0	1	0	0	0	0	0	0
DK	0	0	1	0	0	0	0	0	0
EE	0	0	0	0	0	1	0	0	0
ES	0	0	1	0	0	0	0	0	0
FI	0	0	1	0	0	0	0	0	0
FR	0	0	1	0	0	0	0	0	0
GR	0	0	1	0	0	0	0	0	0
HU	0	0	1	0	0	0	0	0	0
IE	0	0	1	0	0	0	0	0	0
IT	0	0	1	0	0	0	0	0	0
LT	0	0	1	0	0	0	0	0	0
LU	0	0	1	0	0	0	0	0	0
LV	0	0	0	0	0	1	0	0	0
MT	0	0	0	0	0	1	0	0	0
NL	0	0	1	0	0	0	0	0	0
PL	0	0	1	0	0	0	0	0	0
PT	0	0	1	0	0	0	0	0	0
RO	0	0	0	0	0	1	0	0	0
SE	0	0	1	0	0	0	0	0	0
SI	0	0	0	0	0	1	0	0	0
SK	0	0	1	0	0	0	0	0	0
GB	0	0	1	0	0	0	0	0	0
US	0	0	0	1	0	0	0	0	0
JP	0	0	0	0	1	0	0	0	0
CN	1	0	0	0	0	0	0	0	0
CA	0	0	0	1	0	0	0	0	0
KR	0	0	0	0	1	0	0	0	0
BR	0	0	0	0	0	0	1	0	0
IN	0	1	0	0	0	0	0	0	0
MX	0	0	0	1	0	0	0	0	0
RU	0	0	0	0	0	1	0	0	0
AU	0	0	0	0	1	0	0	0	0

CH	0	0	1	0	0	0	0	0	0
TR	0	0	1	0	0	0	0	0	0
TW	0	0	0	0	0	0	0	1	0
NO	0	0	1	0	0	0	0	0	0
ID	0	0	0	0	0	0	0	1	0
ZA	0	0	0	0	0	0	0	0	1
RoW	0	0	0	0	**1**	0	**1**	**1**	**1**

The last country in the 44x44 model is the rest of world, 150 countries that fit into 4 of the 9 regions: OECD Pacific, Latin America, Other developing Asia, and Africa and the Middle East. The RoW is distributed amongst these 4 regions, according to the output of the these regions for the model years. For example, if Latin America accounts for 50% of the sum total output from these 4 sectors in a given year, it is assumed to account for 50% of the RoW ouput for that year, and the value of RoW row, Latin America column of the correspondence matrix would be 0.5.